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DIFFUSION IN LIQUID METAL SYSTEMS

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FINAL REPORT

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SUMMARY

This is the Final Report on NASA Contract NAS8-30252, Diffusion In Liquid Metal Systems. Physical properties of twenty liquid metals are reported in Section I of this handbook in Table 1 to Table 20, starting with aluminum and ending with zinc. Thereafter, some of the data on such liquid metal properties as density, electrical resistivity, thermal conductivity, and heat capacity are summarized in graphical form in Figure 1 through Fig. 14. Data on laboratory handling and safety procedure are also summarized for each metal. Heat-transfer-correlations for liquid metals under various conditions of laminar and turbulent flow are summarized in Section II of this handbook. Where sufficient data have been available, temperature equations of properties have been obtained by the method of least-squares fit. Such equations are given for the appropriate metals in the tables of properties. All values of properties given in this report are valid in the given liquid phase ranges only. Additional tabular data on some 40 metals are reported in Appendix A.

Included in Section III of this handbook is also a brief description of experiments that were performed under Contract NAS8-30252 to investigate diffusion in liquid indium-gallium systems. Considerable difficulty was encountered in the experimentation that resulted in delays in the completion time of this study. The porous disks used in the experiments had to be custom made for this study and were delivered by the manufacturer late. In addition, the disks had a tendency to float in the gallium-indium solutions instead of sinking in them. Considerable time was spent in testing and identifying a suitable weight-sinker material that would be inert in gallium-indium solutions. The solutions coated the walls of glass containers to give mirror surfaces; yet the solutions wetted the porous porcelain disks with only considerable difficulty. Thus, it was difficult to get sufficient amounts of the solutions to be absorbed to yield meaningful measurable variations in weight as diffusion progressed. The values of diffusion coefficients that were determined by this experiment were independent of concentration for indium concentrations less than In 2: Ga 15. Atempts to weigh the porous disks as they were immersed in solution proved futile because of oscillations and sometimes the surface tension in the viscous solutions. Therefore the results reported here were obtained by weighing the disks in air and reimmersing them for predetermined time intervals to permit diffusion in the solution before the next weighing in air.

A temperature-dependent equation was derived for coefficient of diffusion by experiment as $D = D_0 \exp(-\frac{Q}{RT})$ cm^2/sec

D_o = 8.563×10^{-5} cm^2/sec

Q = 1028 cal/gmol

R = 1.987 cal/(gmol-°K)

T = temperature (°K)

INTRODUCTION

It is difficult for many scientists to locate the physical properties of liquid metals without extensive literature search or involved personal correspondence with companies that deal in particular metals. The reason for this difficulty is that, whereas there is a lot of data in the literature on the properties of solid metals, the data for the liquid phase is very scanty indeed. Insufficient experimentation in the molten or liquid state has been carried out to determine such physical properties as liquid density, diffusion coefficient, electrical resistivity, surface tension, thermal conductivity etc.

One of the objectives of this study performed under NASA Contract NAS8-30252 was to cull from the literature such data as are available on the properties of liquid metal, edit them for consistency and acceptability and compile them into a concise booklet that could form easy reference for scientists interested in liquid metals. Another objective of this study was to measure experimentally the mass diffusivity when a gallium-indium solution of known concentration diffused into liquid gallium.

Both objectives have been realized. This report contains a concise booklet (Sections I and II), in which are tabulated physical properties of about 20 liquid metals. A diffusion coefficient $D = 8.563(10^{-5}) \exp(-\frac{1028}{RT})$ cm^2/sec was determined by experiment for the diffusion of a gallium-indium solution of 11.92% indium by weight into pure liquid gallium. RT in the equation for D has units of cal/g-mol. The results of the experimentation are summarized in Section III.

PROPERTIES OF LIQUID METALS

Some properties of liquid metals are summarized in Table 1 to Table 20 for twenty metals. Each table is for one metal starting with aluminum and ending with zinc. It must be emphasized that the properties tabled in this section are for liquid metals only and not solid metals. It must also be emphasized that these tables are by no means exhaustive of all the properties found in the literature. Indeed, they represent the most reliable and consistent values culled from the literature. Where data from some sources have been found too deviant from the general trend of the majority of the sources and have not been corroborated by other independent sources, such data have not been reported. As of now some properties of some liquid metals have been difficult to locate. Additional property data for some 40 metals are included in Appendix A.

Melting point and boiling point data have been taken from Reference 4, because they have been found to agree as well as values found from other sources. Included here are best data from the literature on density, electrical resistivity, heat capacity, and thermal conductivity. A summary of laboratory handling and safety procedure and corrosion information is also reported for each metal. The reported properties-temperature correlations have been obtained by the least-square-method fit of data available. The following units have been used in reporting data:

Temperature (t)	Degree Centigrade	°C
Density (d)	Kilogram per cubic meter	Kg/m^3
Elect. Resistivity (r)	Micro-ohm-centimeter	μohm-cm
Heat Capacity (C_p)	Cal per kilogram per °C	Cal/(Kg-°C)
Thermal Conductivity (K)	Cal per meter per second per °C	Cal/(m-sec-°C)
Latent Heat of Fusion (H_f)	Kilo cal per kilogram	Kcal/Kg
Latent Heat of Vap (H_v)	Kilo cal per kilogram	Kcal/Kg
Viscosity (μ)	Centipoise	cp
Surface tension (γ)	Dyne per meter	dyn/m
Volume Change on Fusion	Percent of solution volume	%

Table 1. ALUMINUM (Al)

Description: A silvery white metal of group IIIA of the Periodic Table of the elements. Atomic weight 26.9815; atomic no. 13; valence 3.

	Ref.
Melting Point (°C): 660.2	4, 7
Boiling Point (°C): 2,467	4
Density (Kg/m): 2558 - 0.27t; 662°C < t < 1100°C. 2369 at 700°C; 2315 (900°C); 2261 (1100°C)	11
Electrical Resistivity (μohm-cm): 11.455 + 0.0135t. 670°C < t < 870°C	7
Heat Capacity (Cal/Kg-°C): 259; 660°C < t < 1000°C	7, 12
Latent Heat of Fusion (Kcal/Kg) 96	35
Latent Heat of Vaporization (Kcal/Kg) 3050	35
Thermal Conductivity (Cal/m-sec-°C): 24.7 (700°C); 29.0 (790°C).	7
Surface Tension (dyn/m) 52,000 (20°C)	35
Viscosity (cp) 2.9 (700°C), 1.4 (800°C)	35
Volume Change (% Sol vol) +6.6	35

Laboratory Handling and Safety Procedure:
Aluminum is nontoxic as evidenced by the widespread use of aluminum cooking untensils and cans. Molten aluminum may be handled in graphite vessels. The only refractories which appear to be inert to molten aluminum at temperatures above but near 100°C are pure, fused, or highly sintered alumina or beryllia. Alluminum oxide is the most stable compound of aluminum and is more stable than the oxides of most other metals. Graphite vessels with a layer of aluminum carbide can be used to contain molten aluminum up to 1800°C.

Corrosion: Molten aluminum attacks all known metals and metal alloys. The most resistant is ordinary gray cast iron probably due to the formation of a barrier of aluminum carbide from the carbon left when the iron is dissolved. Metal equipment may be used with aluminum after first coating with lime, alumina or magnesia and thoroughly drying. Molten Al will react with all oxygen-containing gases, chlorine-containing gases and with nitrogen-containing gases such as ammonia. Thus, the inert gases must be used as atmosphere for liquid aluminum if the aforementioned reactions are to be avoided.

Table 2. ANTIMON. (Sb)

Description: Antimony occurs in four allotropic forms: yellow antimony, black antimony, explosive antimony, and metallic antimony. Metallic antimony is an extremely brittle metal of a flaky, crystalline texture, blue-white color and metallic luster. Sb is a Group VA element with atomic weight 121.75, atomic no. 51, and valence 3 or 5.

Property	Ref.
Melting Point (°C): 630.5	4, 7
Boiling Point (°C): 1750	4
Density (Kg/m^3): $6940 - 0.7t$ $640 < t < 970$ 6490 (640°C), 6450 (700°C) 6380 (800°C)	13
Electrical Resistivity (μohm-cm): $700°C < t < 900°C$ $-1172.81 + 5.09t - 6.71 \times 10^{-3}t^2 + 2.96 \times 10^{-6}t^3$	
Heat Capacity (Cal/Kg-°C): 65.6 $650°C < t < 950°C$	14
Latent Heat of Fusion (Kcal/Kg) 38.3	35
Latent Heat of Vaporization (Kcal/Kg) 383	35
Thermal Conductivity (Cal/m-sec-°C): 5; $650°C < t < 730°C$	
Surface Tension (dyn/m) 38,300 (635°C), 38,400 (675°C), 38,300 (725°C), 38,000 (800°C)	35
Viscosity (cp) 1.296 (702°C), 1.113 (801°C), 0.994 (900°C), 0.905 (1002°C)	35
Volume Change (% Sol vol) -0.94	35

Laboratory Handling and Safety Procedure: The toxicity of antimony is of the same order of magnitude as that of arsenic. It is highly poisonous. Sb compounds such as the oxide can cause an irritating skin rash. Ventillation must be provided to carry off any fume from liquid antimony. Recommended maximum allowable concentration of antimony dust in air is 0.5 mg/m^3 of air. Cast iron and mild steel have been found satisfactory for containing antimony; but inconel, monel and nickel should not be used. Water or water vapor react readily with molten antimony forming Sb_2O_3 and hydrogen.

Table 3. BISMUTH (Bi)

Description: Bismuth is a white, crystalline, brittle metal with a pinkish tinge. It is the most diamagnetic of all metals and its thermal conductivity is lower than that of any metal except mercury. It has the highest Hall effect of any metal--the ability to increase its electrical resistance in the presence of a magnet. Bismuth expands 3.32% on solidification. It is a Group VA element with atomic weight 208.90, atomic number 83, and valence 3 or 5.

	Ref.
Melting Point (°C) 271	4
Boiling Point (°C): 1477	4, 7
Density (Kg/m^3): 10450 - 1.32t 300°C < t < 1000°C 10020 (300°C), 9910 (400°C), 9660 (600°C)	7,13,25
Electrical Resistivity (μohm-cm): 128.9 (300°C), 134.2 (400°C), 145.15 (600°C), 153.53 (750°C)	7
Heat Capacity (Cal/Kg-°C): 36.0 280°C < t < 700°C	25
Latent Heat of Fusion (Kcal/Kg) 12.0	35
Latent Heat of Vaporization (Kcal/Kg) 204.3	35
Thermal Conductivity (Cal/m-sec-°C):	
3.7 400°C < t < 700°C	7
3.5 (300°C), 3.7222 (400°C), 4.25 (650°C)	25
Surface Tension (dyn/m) 37,6000 (300°C); 37,300 (350°C), 37,000 (400°C), 36,700 (450°C), 36,300 (500°C)	35
Viscosity (cp) 1.662 (304°C), 1.280 (451°C), 0.996 (600°C)	35
Volume Change (% Sol vol) -3.32	35

Laboratory Handling and Safety Procedure: Commercial aluminum has been recommended for handling liquid bismuth, but platinum, inconel, and nickel are not recommended. Bismuth oxidizes superficially in moist air at room temperatures, forming an oxide film which protects it from further oxidation. Adequate ventilation must be provided to ensure that workmen do not breathe fumes from molten or burning bismuth. There are no recorded cases of poisoning by bismuth metal. However, bismuth is apt to be stored in diseased tissue.

Table 4. CADMIUM (Cd)

Description: Cadmium is a soft bluish-white metal which is easily cut with a knife. It is similar in many respects to zinc. Cadmium and its compounds are toxic. Cd is a Group IIB element of atomic weight 112.40, atomic number 48, and valence 2.

	Ref.
Melting Point: 321.09°C	4
Boiling Point (°C): 765	4, 7
Density Kg/m³): 801 (330°C), 793 (400°C), 772 (600°C)	13
Electrical Resistivity (μohm-cm): 33.7 (325°C) 33.7 (400°C), 34.12 (500°C), 34.82 (600°C), 35.78 (700°C)	7
Heat Capacity (Cal/Kg-°C): 63.2 322°C < t < 1000°C	7
Latent Heat of Fusion (Kcal/Kg) 13.2	35
Latent Heat of Vaporization (Kcal/Kg) 286.4	35
Thermal Conductivity (Cal/m-sec- C): 10.50 355°C < t < 380°C 11.9 (435°C)	7
Surface Tension (dyn/m) 56,400 (330°C); 60,800 (370°C) 59,800 (420°C); 61,100 (450°C); 60,000 (500°C)	35
Viscosity (cp) 2.37 (350°C); 2.16 (400°C); 1.84 (500°C); 1.54 (600°C)	35
Vol Change (% Sol vol) +4.74	35

Laboratory Handling and Safety Procedure: Cadmium and its compounds are toxic and must be handled with extreme care. The recommended maximum allowable concentration of cadmium vapor in air is 0.1 mg/m³ of air. Cast iron has been used most frequently for handling liquid cadmium. Stainless steels are moderately attacked by liquid cadmium.

Table 5 CALCIUM (Ca)

Description: Calcium is a rather hard metal that is silvery in color. It is an alkaline earth metal. Calcium reacts with water, burns with a yellow red flame forming largely calcium nitride. It is a Group IIA element with atomic weight 40.08, atomic number 20, and valence 2.

Property	Value	Ref.
Melting Point (°C):	842	4
Boiling Point (°C):	1487	4
Density (Kg/m^3):	-	
Electrical Resistivity (μohm-cm):	-	
Heat Capacity (Cal/Kg-°C):	190 (851°C $\leq t \leq$ 1200°C)	36
Latent Heat of Fusion (Kcal/Kg)	55.64	36
Latent Heat of Vaporization (Kcal/Kg)	915.67	36
Thermal Conductivity (Cal/m-sec-°C):	-	
Surface Tension (dyn/m)	25,500	36
Laboratory Handling and Safety Procedure	-	

Table 6. CESIUM (Cs)

Description: Cesium is an alkali metal isolated usually by electrolysis of its fused cyanide. It is silvery-white, soft and ductile. It is the most electropositive and most alkaline element. Cesium is liquid at room temperatures. It is a Group IA element with atomic weight 132.905, atomic number 55, and valence 1.

Property	Value	Ref.
Melting Point (°C):	28.40 ± 0.10	4
Boiling Point (°C):	678.4	4
Density (Kg/m^3):	1848 at melting point	
Electrical Resistivity (μohm-cm):	36.6 (30°C), 37.0 (37°C)	7
Heat Capacity (Cal/Kg-°C):	60.0 at melting point	7
Latent Heat of Fusion (Kcal/Kg)	3.766	35
Latent Heat of Vaporization (Kcal/Kg)	146.0	35
Thermal Conductivity (cal/m-sec-°C):	4.4 at melting point	
Surface Tension (dyn/m)	-	
Viscosity (cp)	0.6299 (43.4°C); 0.4753 (99.6°C) 0.4065 (140.5°C); 0.3750 (168.0°C); 0.3430 (210.9°C)	35
Volume Change (% Sol vol)	+2.6	35

Laboratory Handling and Safety Procedure: Cesium catches fire in dry air and in general reacts the same way as the other alkali metals. Therefore, it is handled with the same precautions as are used for other alkali metals such as Li, K, and Na. No information has yet been located on the toxicity of Cesium.

Table 7. GALLIUM (Ga)

Description: Gallium is a gray white metal of Group IIIA of the periodic table of elements. It has atomic weight 69.72, atomic number 31, and valence 2 or 3.

		Ref.
Melting Point (°C):	29.78	4,5,6
Boiling Point (°C):	2403	4
Density (Kg/m^3):	$6105 - 0.691t + 8.3 \times 10^{-5}t^2$ $30°C < t < 1100°C$. 6093 (32.38°C), 5720 (600°C), 5445 (1100°C).	6,7,8,9
Electrical Resistivity (μohm-cm):	$24.9 + 0.076t$ $30°C < t < 46°C$	7
Heat Capacity (Cal/Kg-°C):	82.0 $30°C < t < 1100°C$	7
Latent Heat of Fusion (Kcal/Kg)	19.16	35
Latent Heat of Vaporization (Kcal/Kg)	1014.0	35
Thermal Conductivity (Cal/m-sec-°C):	7 to 9 at melt point	7, 10
Surface Tension (dyn/m)	73,500; $30°C \leq t \leq 40°C$	35
Volume Change (% Sol vol)	-3.1	35

Laboratory Handling and Safety Procedure: Information on the toxicity of gallium is scanty. It appears to be non-poisonous. Gallium and Gallium Nitrate are essentially nontoxic. Gallium may be regarded as being of low toxicity of the order of that of aluminum [4,7]. Gallium is essentially a liquid at room temperatures and has an extremely low vapor pressure. Gallium expands on freezing; hence, it should not be packed in glass bottles. Samples have been packed in rubber bulbs. Gallium wets glass, most probably due to gallium oxides. Wetting of glass by Ga may be prevented by a layer of distilled water or a layer of paraffin.

Corrosion: Liquid gallium is very corrosive at high temperatures. This characteristic limits its use at high temperatures. A small pellet of gallium which melted on a laboratory balance caused severe pitting of the pan although the melt was removed promptly [7]. However, at room temperatures, the corrosion of gallium in air, and a sulfur dioxide atmosphere has been found to be negligible. The corrosion rates in air become appreciable above 400°C. In tests at 700°C, the corrosion rate remained constant for a period of time, and then,

Table 7 (cont'd) GALLIUM (Ga)

increased rapidly with conversion of the entire sample to the oxide, indicating that the formation of a critical amount of oxide was necessary to accelerate corrosion. Ga metal may be handled in quartz to temperatures near its melting point since it does not appear to reduce quartz. From the scanty information on gallium, there are indications that liquid gallium attacks nearly all metals, as does molten aluminum. Tantalum, zirconium, and tungsten, however, resist attack by gallium at several hundred degrees for an appreciable time.

Table 8. GOLD (Au)

Description: Gold is a yellow metal when in mass, but when finely divided, it may be black, ruby or purple in color. Auric gold is tested by the delicate Purple of Cassius test. Gold is a soft metal and it is the most malleable and ductile metal. An ounce of gold can be beaten out to 300 sq. ft. A mixture of $1HNO_3$:3HCl is called aqua regia because it dissolves gold, the king of metals. Gold is a group IB element with atomic weight 196.967, atomic number 79, and valence 1 or 3.

		Ref.
Melting Point (°C):	1063	4, 7
Boiling Point (°C):	2966	4, 7
Density (Kg/m^3):	17240 (1100°C), 17120 (1200°C) 17000 (1300°C)	
Electrical Resistivity (μohm-cm):	31.34 (1100°C), 34.17 (1300°C) 37.00 (1500°C)	
Heat Capacity (Cal/Kg-°C):	35.5 1063 < t < 1300°C	7
Latent Heat of Fusion (Kcal/Kg)	19.16	35
Latent Heat of Vaporization (Kcal/Kg)	1014.0	35
Thermal Conductivity:	No data have been located yet.	
Surface Tension (dyn/m)	73,500; 30°C < t < 40°C	35
Viscosity (cp)	-	
Volume Change (% Sol vol)	+5.195	35

Laboratory Handling and Safety Procedure: Gold is extremely inactive. However, it is dissolved by aqua regia (1 part concentrated nitric acid and 3 parts concentrated hydrochloric acid). Molten gold is immiscible with boron, hydrogen, sulfur, and molybdenum. Liquid gold dissolves most other elements to varying degrees. Contamination of molten gold with base metals like lead and bismuth ought to be avoided, and the atmosphere surrounding molten gold should be kept oxidizing. Traces of lead and bismuth make gold very brittle. The vapor pressure of gold is very low. No toxicity of any significance has been reported from its use in dental fillings.

Table 9. INDIUM (In)

Description: Indium is a Group IIIA element with atomic weight 114.82, atomic number 49, and valence 1, 2, or 3. It is a very soft silvery -white metal with a brilliant luster. It emits a high-pitched "cry" when a rod of the pure metal is bent.

	Ref.
Melting Point (°C): 156.4	4, 7
Boiling Point (°C): 2087	4, 7
Density (Kg/m^3): $156.4 < t < 300°C$ $7159.6 - 0.813t$	7, 26
Electrical Resistivity (μohm-cm): 29.10 (154°C) 30.11 (181.5°C, 31.87 (222°C), 34.84 (280.2°C)	7
Heat Capacity (Cal/Kg-°C): 65.2 (156.4°C)	
Latent of Fusion (Kcal/Kg) 6.807	35
Latent Heat of Vaporization (Kcal/Kg) 468	35
Thermal Conductivity (Cal/m-sec-°C): 9 to 12 at melting point.	
Surface Tension (dyn/m) 34,000 ($170°C < t < 250°C$)	35
60,200 - 10T T = °K	36
Viscosity -	
Volume Change (% Sol vol) +2.5	35

Laboratory Handling and Procedure: There is evidence that indium is toxic and may be potentially hazardous to workers under certain conditions. Indium attacks cast iron only moderately, but reacts easily with nickel and monel. Indium wets glass, as gallium does. Indium can be plated onto metal and evaporated onto glass forming a mirror as good as that made with silver, but with more resistance to atmospheric corrosion. Adequate ventillation should be provided when molten indium is handled. The basic lesion of poisoning by indium seems to be degeneration of liver and kidney. However, personnel who have worked with indium and indium compounds for 20 years have noted no dermatitis or toxic reaction.

Table 10. LEAD (Pb)

Description: Lead is a Group IVA metal with atomic weight 207.19, atomic number 82, and valence 2 or 4. It is a bluish-white metal of bright luster, very soft, highly malleable, is dictile, and a poor conductor of electricity. Lead is toxic. Lead poison gradually disappears from the body if the source of exposure is removed. On the other hand, lead poison is cumulative in the body.

	Ref.
Melting Point (°C): 327.4	4, 7
Boiling Point (°C): 1744	4
Density (Kg/m^3): 10510 (400°C), 10390 (500°C) 10270 (600°C), 10040 (800°C), 9810 (1000°C)	7,27,28
Electrical Resistivity (μohm-cm): 94.6 (327°C), 98.0 (400°C) 107.2 (600°C), 116.4 (8000°C), 125.7 (1000°C)	
Heat Capacity (Cal/Kg-°C): 35.2 400°C < t < 800°C	25
Latent Heat of Fusion (Kcal/Kg) 5.89	35
Latent Heat of Vaporization Kcal/Kg) 204.6	35
Thermal Conductivity (Cal/m-sec-°C): 3.6111 (400 °C) 3.694 (500°C), 3.8055 (600°C), 4.7222 (800°C)	25
Surface Tension dyn/m) 44,200 (350°C); 43,800 (400°C) 43,800 (450°C) 43,100 (500°C)	35
Viscosity (cp) 2.116 (441°C); 2.059 (456°C); 1.700 (551°C); 1.349 (703°C); 1.185 (844°C)	
Volume Change (% Sol vol) +3.6	

Laboratory Handling and Procedure: All forms of lead are potentially toxic. However, lead poisoning occurs most commonly after the inhalation or ingestion of lead fumes or very fine lead dusts. The risk of serious poisoning increases with the reduction in particle size, and inhaled lead is more toxic than swallowed lead. Lead poison is cumulative. Adequate ventillation and cleanliness and periodic examination of personnel for lead count should be rigorously maintained. The concentration of lead fumes should be kept below 0.15 mg/m^3 of air. Liquid lead is handled in regular production practice by pumping with immersed cast-iron centrifugal pumps. Cast-iron, medium-carbon cast-steel and welded-steel containers are used regularly for liquid lead. Lead is intself very resistant to corrosion; hence, its wide-spread use in piping.

Table 11 LITHIUM (Li)

Description: Lithium is a Group IA element of atomic weight 6.939, atomic number 3, and valence 1. Lithium is silvery in appearance like Na and K, other members of the alkali metal series. Li is the least dense of the normally solid elements, and it is the least reactive of the alkali metals. It reacts only slowly with cold water, because it becomes quickly coated with insoluble lithium hydroxide.

	Ref.
Melting Point (°C): 180.54	4
Boiling Point (°C): 1317	4, 7
Density (Kg/m^3): 510 (250°C), 495 (400°C) 484 (500°C), 474 (600°C), 465 (700°C)	25
Electrical Resistivity (μohm-cm): 45.25 (230°C)	7
Heat Capacity (Cal/Kg-°C): 1000 200°C < t < 1000°C	7
Latent Heat of Fusion (Kcal/Kg) 158	35
Latent Heat of Vaporization (Kcal/Kg) 4680	35
Thermal Conductivity (Cal/m-sec-°C): 11.055 (250°C), 11.25 (400°C), 11.3611 (500°C), 11.4722 (600°C), 11.5833 (700°C)	25
Surface Tension (dyn/m) -	
Viscosity (cp) 0.5918 (183.4°C); 0.5749 (193.2°C); 05541 (208.1°C); 0.4917 (250.8°C); 0.4548 (285.5°C)	35
Volume Change (% Sol vol) +1.5	

Laboratory Handling and Procedure: Lithium cannot be melted in glass or in the usual laboratory ceramics because it severly attacks them. The inert gases should be used to provide atmosphere for handling molten lithium up to 500°C; beyond that, steels become decarburized. Persons handling liquid Li should be protected against leakage or spattering by using a face-and-head shield in the form of a "cage" made of 14-mesh steel-wire screen. The cage fits loosely over the head and rests on the shoulders and may be extended in front as a bib to protect the chest. The shield thus formed is cool and lightweight. A swab moistened with 80 per cent ethyl alcohol should be used to wash away the residues on a burn on a moist skin by lithium. Lithium fires should be smothered with graphite powder, not sand. Burning lithium reacts with sand.

Table 12. MAGNESIUM (Mg)

Description: Magnesium is a Group IIA element with atomic weight 24.312, atomic number 12, and valence 2. It is a light, silvery white, and fairly tough metal. Finely-divided magnesium readily ignites upon heating in air and burns with a dazzling white flame.

		Ref.
Melting Point (°C):	651	4, 7
Boiling Point (°C):	1107	4
Density (Kg/m^3):	1572 (651°C), 1550 (678°C), 1536 (700°C), 1510 (720°C), 1470 (750°C)	7
Electrical Resistivity (μohm-cm):	No data have been located.	
Heat Capacity (Cal/Kg-°C):	317 (651°C), 321 (727°C), 332 (927°C), 337 (1027°C), 342 (1120°C)	
Latent Heat of Fusion (Kcal/Kg)	82.2	35
Latent Heat of Vaporization (Kcal/Kg)	1337	35
Thermal Conductivity (Cal/m-sec°C):	No data have been located.	
Surface Tension (dyn/m)	-	
Viscosity (cp)	-	
Volume Change (% Sol Vol.)	+4.2	35

Laboratory Handling and Procedure: Great care should be taken in handling magnesium, especially in the finely divided form, as serious fires can occur. Water should not be used on burning magnesium or on magnesium fires. Molten magnesium does not react with carbon or silicon carbide. It hardly attacks molybdenum or tantalum. Steel and iron may be used as containers for molten magnesium because they have only weak reactions with magnesium. Between 700°C and 750°C, saturation concentration for iron dissolved in magnesium is only about 0.04%. As long as a uniform temperature is maintained after saturation has been reached, no more iron would dissolve. Fire proof clothing, gloves and shoes should be worn when working with molten magnesium.

Table 13. MERCURY (Hg)

Description: Mercury is a Group IIB element with atomic weight 200.59, atomic number 80, and valence 1 or 2. Mercury is a heavy silvery white liquid metal at room temperatures. Mercury is a poor conductor of heat as compared to other metals. It is a fair conductor of electricity.

Property	Value	Ref.
Melting Point (°C):	-38.87	4, 7
Boiling Point (°C):	356.58	4
Density (Kg/m^3):	13645 (-20°C), 13590 (0°C), 13550 (20°C) 13230 (150°C), 13110 (200°C), 12880 (300°C)	7, 25
Electrical Resistivity (μohm-cm):	98.4 (50°C), 103.2 (100°C) 114.2 (200°C), 127.5 (300°C), 135.5 (350°C)	
Heat Capacity (Cal/Kg-°C):	33.34 (0°C), 32.9 (50°C), 32.8 (100°C)	7 25
Latent Heat of Fusion (Kcal/Kg)	2.8	35
Latent Heat of Vaporization (Kcal/Kg)	1337	35
Thermal Conductivity (Cal/m-sec-°C):	1.96 (0°C), 2.31 (60°C) 2.61 (120°C), 2.79 (160°C), 3.03 (220°C)	7
Surface Tension (dyn/m)	46,500 (20°C); 45,400 (112°C); 43,600 (200°C); 40,500 (300°C); 39,400 (354°C)	35
Viscosity (cp)	1.85 (-20°C); 1.68 (0°C); 1.55 (20°C); 1.21 (100°C); 1.01 (200°C)	35
Volume Change (% Sol vol.)	+3.6	35

Laboratory Handling and Procedure: Mercury is a virulent poison, and is readily absorbed through the respiratory tract, the gastrointestinal tract, or through unbroken skin. It is cumulative in the human system. The maximum allowable concentration of mercury vapor in air is 0.1 mg/m^3 of air. Since mercury is a very volatile element, it must be handled with the utmost care. If it is necessary to heat mercury, the heating should be done in a well ventilated hood. Hg is usually handled in the laboratory in glass containers, but it can be put in iron or stainless steel vessels. Iodized carbon filters have been recommended as absorbents of mercury. A 20 percent solution of $FeCl_3$ (ferric chloride) has been reported to be most effective decontaminant for mercury drops.

Table 14. POTASSIUM (K)

Description: A soft and easily cut metal, potassium has a silvery appearance. It is one of the most reactive and electropositive of metals. Except for lithium, it is the lightest metal known. Potassium and its salts impart a violet color to flames. It catches fire spontaneously with water. Potassium is a Group IA element with atomic weight 39.102, atomic number 19, and valence 1.

	Ref.
Melting Point (°C): 63.63	4,7
Boiling Point (°C) 774	4
Density (kg/m³): $841.5 - 0.2172t - 2.70 \times 10^{-5}t^2 + 4.77 \times 10^{-9}t^3$ $64°C < t < 1250°C$ 783 (250°C), 747 (400°C)	20
Electrical Resistivity (μohm-cm): $93.3°C < t < 1933.3°C$ $7.9898+6.373\times10^{-2}t-1.3959\times10^{-5}t^2+5.301969\times10^{-8}t^3$	21
Heat Capacity (Cal/Kg-°C): $64 < t < 770°C$ $200.4 - 0.08777t + 1.097 \times 10^{-4}t^2$	17,19, 22,23
Latent Heat of Fusion (Kcal/Kg) 14.6	35
Latent Heat of Vaporization (Kcal/Kg) 496	35
Thermal Conductivity (Cal/m-sec-°C): $100°C < t < 800°C$ $10.454 - 5.298 \times 10^{-3}t + 2828.2/T$ where $T = t + 273.2$	19
Surface Tension (dyn/m) 8,600 ($100°C < t < 150°C$)	35
Viscosity (cp) 0.515 (69.6°C); 0.331 (167.4°C); 0.258 (250°C) 0.191 (400°C); 0.136 (700°C)	35
Volume Change (% Sol Vol) +2.41	35

Laboratory Handling and Safety Procedure: Potassium oxidizes rapidly in air and must be preserved in a mineral oil such as kerozene. It ignites spontaneously in water and must therefore be kept away from water. Potassium should be handled as described for sodium, with the realization that potassium is more reactive than sodium. Potassium ion is somewhat toxic [24].

Table 15 RUBIDIUM (Rb)

<u>Description</u>: Rubidium is a group IA element with atomic weight 85.47, atomic number 37, and valence 1, 2, 3, 4. It can be liquid at room temperature. Rb is a soft, silvery-white metal of the alkali metal group. Naturally occurring Rb has two isotopes one of which (Rb-85) is sufficiently radioactive to expose a photographic film in 30 days. Rb-85 is the isotope that composes 72% of natural rubidium. The remaining 28% of natural rubidium is Rb-87, a beta emitter with a half life of 6×10^{10} years.

	Ref.
<u>Melting Point</u> (°C): 39	4, 7
<u>Boiling Point</u> (°C): 688	4, 7
<u>Density</u> (Kg/m³): 1475 (39°C)	
<u>Electrical Resistivity</u> (μohm-cm): 23.25 (50°C), 25.32 (75°C) 24.47 (100°C)	
<u>Heat Capacity</u> (Cal/Kg-°C): 91.3 39°C < t < 126°C 92.1 - 0.026t	7
<u>Latent Heat of Fusion</u> (Kcal/Kg) 6.1	35
<u>Latent Heat of Vaporization</u> (Kcal/Kg) 212	35
<u>Thermal Conductivity</u> (Cal/m-sec-°C): 7.0 (39°C) 7.5 (50°C)	7
<u>Surface Tension</u> (dyn/m) 92,300 (995°C)	35
<u>Viscosity</u> (cp) 2.98 (1200°C)	35
<u>Volume Change on Fusion</u> (% Sol Vol) +4.99	35

<u>Laboratory Handling and Procedure</u>: Rubidium may be handled in a manner similar to that described for sodium (Table 17). Consideration should be given to the fact that rubidium will ignite spontaneously in air. The same precautions for safety should be observed with rubidium as is described for sodium. In particular, protective clothing and body covering should be worn by persons working with liquid rubidium.

Table 16. SILVER (Ag)

Description: Silver is a Group IB element with atomic weight 107.87, atomic number 47, and valence 1, 2. Pure silver is a brilliant white lustrous metal. It is a little harder than gold, very ductile and malleable. Silver has the highest electrical and thermal conductivity of all metals when it is in the solid state.

	Ref.
Melting Point (°C): 960.8	4
Boiling Point (°C): 2212	4
Density (Kg/m^3): 9300 (960.8°C), 9260 (1000°C), 9200 (1091°C), 9100 (1195°C), 9000 (1300°C)	7
Electrical Resistivity (μohm-cm): 17.0 (1000°C), 18.2 (1100°C), 19.4 (1200°C), 20.5 (1300°C), 21.0 (1340°C)	29
Heat Capacity (Cal/Kg-°C): 69.2 960.8 < t < 1300°C	7
Latent Heat of Fusion (Kcal/Kg) 24.9	35
Latent Heat of Vaporization (Kcal/Kg) 556	35
Thermal Conductivity (Cal/m-sec-°C): No data have been located.	
Surface Tension (dyn/m) 92,300 (995°C)	35
Viscosity (cp) 2.98 (1200°C)	35
Volume Change on Fusion (% Sol vol) +4.99	35

Laboratory Handling and Procedure: Molten silver is immiscible with iron, cobalt, iridium, tantalum, vanadium, tungsten, germanium, hydrogen, molybdenum, nickel, and rhodium. Most Silver is insoluble in most refractories. Silver and its alloys are regularly melted in crucibles of conventional clay-graphite. Silver salts are poisonous.

Table 17 SODIUM (Na)

Description: A soft bright silvery metal which floats on water, sodium decomposes water with the evolution of the hydroxide of sodium. Sodium may or may not ignite spontaneously in water depending on the amount of the oxide and the metal exposed to the water. Na is a Group IA element with atomic weight 22.9898, atomic number 11, and valence 1.

	Ref.
Melting Point (°C): 97.81 ± 0.03	4
Boiling Point (°C): 892	
Density (Kg/m³): 98°C < t < 1370°C $950.1 - 0.22976t - 1.460 \times 10^{-5}t^2 + 5.638 \times 10^{-9}t^3$; 891 (250°C), 854 (400°C)	15,16
Electrical Resistivity (μohm-cm): 98°C < t < 1100°C $7.756 + 2.05 \times 10^{-2}t + 3.481 \times 10^{-5}t^2$	7,17
Heat Capacity (Cal/Kg-°C): 98°C < t < 900°C $343.24 - 1.3868 \times 10^{-1}t + 1.1044 \times 10^{-4}t^2$	18
Latent Heat of Fusion (Kcal/Kg) 27.05	35
Latent Heat of Vaporization (Kcal/Kg) 1005	35
Thermal Conductivity (Cal/m-sec-°C): 98°C < t < 890°C $21.766 - 0.0117t$	
Surface Tension (dyn/m): 20,640 (100°C); 19,950 (250°C)	35
Viscosity (cp) 0.686 (103.7°C); 0.504 (167.6°C); 0.381 (250°C); 0.269 (400°C); 0.182 (700°C)	35
Volume Change on Fusion (% Sol vol) +2.5	35

Laboratory Handling and Safety Procedure: Personnel handling Na should wear goggles and gloves. All glassware and other equipment should be thoroughly dry. Sodium should be handled with care as it may ignite in air or in water. Carbon tetrachloride should never be brought into contact with sodium. Small amounts of sodium may be removed from glassware by treatment with alcohol in a nitrogen atmosphere. If a relatively large quantity of sodium must be disposed of, a good practice is to burn it in a steel pan over an open flame. Burning Na evolves a heavy smoke which is extremely irritating to the mucuous membrane and moist skin. Personnel exposed to oxide fumes should be equipped with suitable filter type respirators or some other type of respiratory-protective equipment

Table 17 (cont'd). SODIUM (Na)

along with protective clothing. Rubber-coated suits give good protection. Should sodium catch fire, quick action should be taken to cool the sodium and to prevent its access to air. Covering the burning material with dry soda ash or salt is usually sufficient. Sodium bicarbonate must never be used in place of soda ash.

It is recommended that all personnel working with sodium wear some type of head covering as well as face shields and cover the entire body if the possibility exists that liquid sodium may be spilled or ejected from an equipment. Burns produced by contact with sodium are very likely to be infected. If molten sodium is splashed on the skin, it should be removed by flushing with large quantities of water. The residual alkali can be removed with dilute acetic or boric acid, followed by washing with water. The burn should be treated with a salve containing a sulfa drug.

Table 18. THALLIUM (Tl)

Description: Thallium is Group IIIA element which gives beautiful green spectral lines. When freshly exposed to air, Tl exhibits a metallic luster, but soon develops a bluish-gray tinge, resembling lead in appearance. It is a very soft and malleable metal of atomic weight 204.37, atomic number 81, and valence 1 or 3.

	Ref.
Melting Point (°C): 303	4,7
Boiling Point (°C): 1457	4,7
Density (Kg/m^3): 11289 (306.5°C), 11254 (326.7°C), 11250 (330°C), 11254 (333.5°C)	7
Electrical Resistivity (μohm-cm): 74.0 (303°C)	
Heat Capacity (Cal/Kg-°C): 36.7 $303 < t < 500°C$	
Latent Heat of Fusion (Kcal/Kg) 5.04	35
Latent Heat of Vaporization (Kcal/Kg) 189.9	35
Thermal Conductivity (Cal/m-sec-°C): 5.9 (350°C)	
Surface Tension (dyn/m) 40,100 (327°C)	35
Viscosity (cp) -	
Volume Change on Fusion +3.2	35

Laboratory Handling and Safety Procedure: Thallium and its compounds are toxic and should be handled carefully. Contact of the metal with the skin is dangerous and when melting the metal, adequate ventillation should be provided. The maximum allowable concentration of soluble thallium compounds in air is 0.1 mg/m^3 of air. Cast iron has been recommended for the handling of liquid thallium. Because of high rates of attack, nickel and monel are not recommended. A tungsten-sheathed filament has been found satisfactory in determing heat capacities. Thallium poison is cumulative, and being soluble in water in the presence of oxygen, thallium may enter the body system by the skin pore or through cuts and abrasions of the skin.

Table 19. TIN (Sn)

Description: Tin is a Group IVA element with atomic weight 118.69, atomic number 50, and valence 2, 4. Ordinary tin is a silvery white metal, malleable, and ductile, and has a highly crystalline structure. Due to its crystalline structure, tin emits a "tin cry" when a bar is bent. Below 13.2°C, tin turns from white to gray tin.

Property	Ref.
Melting Point (°C): 231.9	4,7
Boiling Point (°C): 2270	4,7
Density (Kg/m^3): 6980 (250°C), 6834 (409°C) 6790 (500°C), 6720 (600°C), 6640 (700°C)	7,25 28
Electrical Resistivity (μohm-cm): 47.6 (231.9°C), 51.4 (400°C) 56.8 (600°C), 62.7 (800°C), 68.6 (1000°C)	7
Heat Capacity (Cal/Kg-°C): 61 240°C < t < 700°C	25,30
Latent Heat of Fusion (Kcal/Kg) 5.04	35
Latent Heat of Vaporization (Kcal/Kg) 189.9	35
Thermal Conductivity (Cal/m-sec-°C): 7.277 (240°C) 7.56 (300°C), 8.4722 (500°C), 9.4166 (700°C)	25
Surface Tension (dyn/m) 52,600 (300°C); 52,200 (350°C); 51,800 (400°C); 51,400 (450°C); 51,000 (500°C)	35
Viscosity (cp) 1.91 (240°C); 1.67 (300°C); 1.38 (400°C) 1.18 (500°C); 1.05 (600°C)	35
Volume Change on Fusion (% Sol Vol) +2.6	35

Laboratory Handling and Procedure: Molten tin is a very corrosive metal. The usual material for handling tin is cast iron. The rate of attack on stainless steel increases with temperature and becomes quite high above 600°C. Nickel, copper, and their alloys are not suitable for handling molten tin. Poisoning from tin is practically unknown. However, suitable ventillation should be provided to remove any fumes formed during the handling of the molten metal.

Table 20. ZINC (Zn)

Description: Zinc is a group IIB metal with atomic weight 65.37, atomic number 30, and valence 2. It is a bluish-white lustrous metal. It is brittle at ordinary temperatures but malleable at 100°C to 150°C. Molten zinc drosses very heavily in air.

	Ref.
Melting Point (°C): 419.5	4,7
Boiling Point (°C): 907	4
Density (Kg/m^3): 6920 (419.5°C), 6810 (600°C) 6570 (800°C)	7
Electrical Resistivity (μohm-cm): 35.3 (419.5°C), 35.4 (500°C), 35.0 (600°C), 35.65 (700°C), 35.7 (800°C)	
Heat Capacity (Cal/Kg-°C): 119.9 (419.5°C), 117.3 (600°C) 107.6 (800°C), 104.4 (900°C)	
Latent Heat of Fusion (Kcal/Kg) 24.4	35
Latent Heat of Vaporization (Kcal/Kg) 419.5	35
Thermal Conductivity (Cal/m-sec-°C): 13.8 (500°C) 13.6 (600°C), 13.5 (700°C)	
Surface Tension (dyn/m) 78,500 (510°C); 77,800 (550°C); 76,800 (600°C); 76,100 (640°C)	35
Viscosity (cp) 3.17 (450°C); 2.78 (500°C); 2.24 (600°C) 1.88 (700°C)	35
Volume Change on Fusion (% Sol vol) +6.9	35

Laboratory Handling and Procedure: In order to prevent zinc dust from catching fire, it must be kept dry and away from vibrations. Molten zinc is very corrosive. Cast iron may be used for handling it if moderate temperatures are employed. Liquid zinc wets tantalum. It attacks stainless steel increasingly as the temperature rises. Stainless steel may not be used above 500°C to keep zinc. However, molten zinc does not attack pure graphite containers. Zinc has a high vapor pressure (about 1/3 atmosphere at 800°C). Hence, precaution must be taken to prevent excessive evaporation of zinc from the melt. Zinc-fume fever is an unpleasant sensation which lasts only a few hours and has no cumulative effect. Average concentration of zinc oxide fumes should be kept below 10 mg per cubic meter of air. Zinc poisons are temporary and seldom acute.

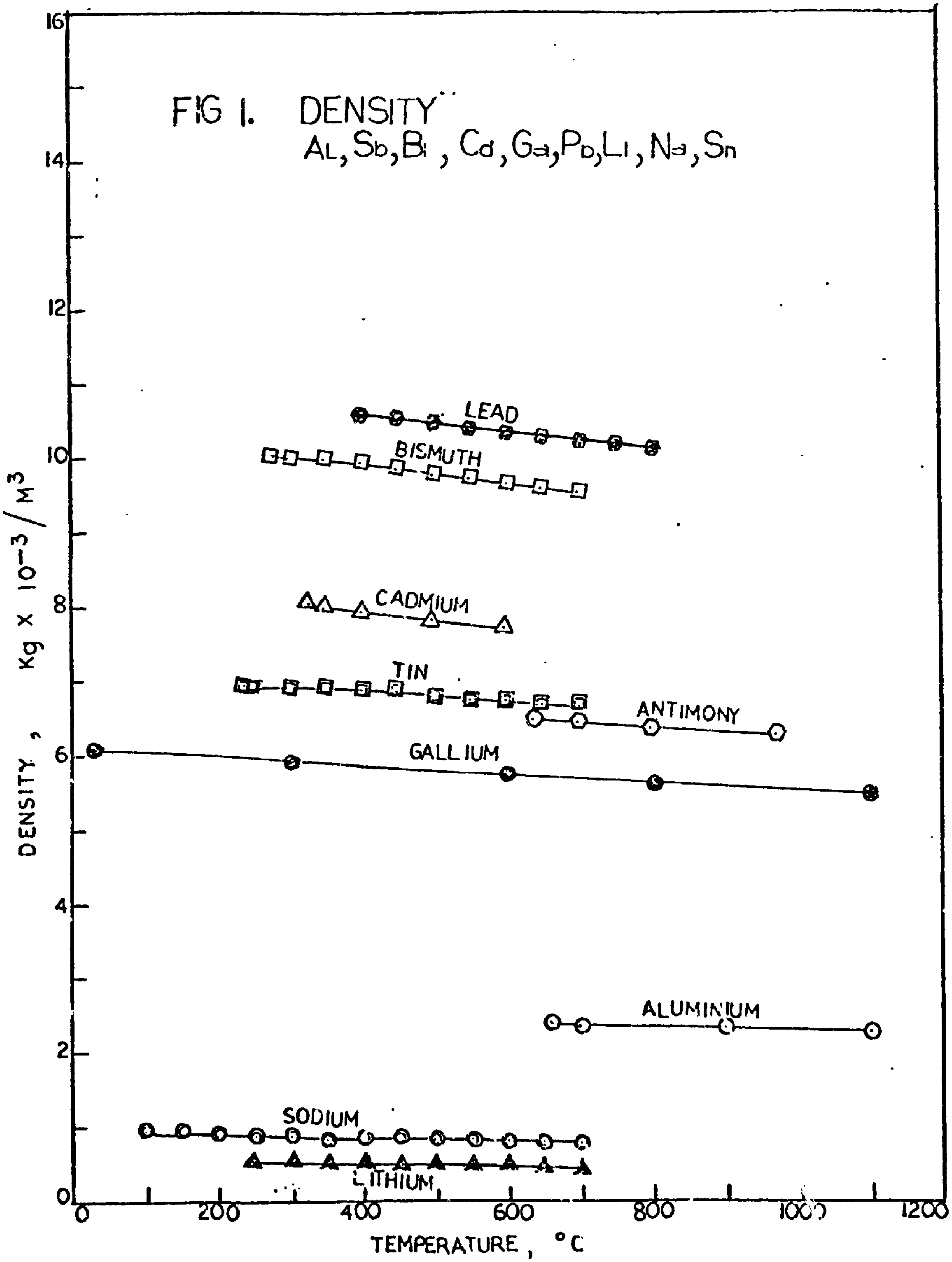


FIG I. DENSITY
AL, Sb, Bi, Cd, Ga, Pb, Li, Na, Sn
LEAD
BISMUTH
CADMIUM
TIN
ANTIMONY
GALLIUM
ALUMINIUM
SODIUM
LITHIUM
DENSITY, Kg X 10⁻³/M³
TEMPERATURE, °C
0
2
4
6
8
10
12
14
16
200
400
600
800
1000
1200

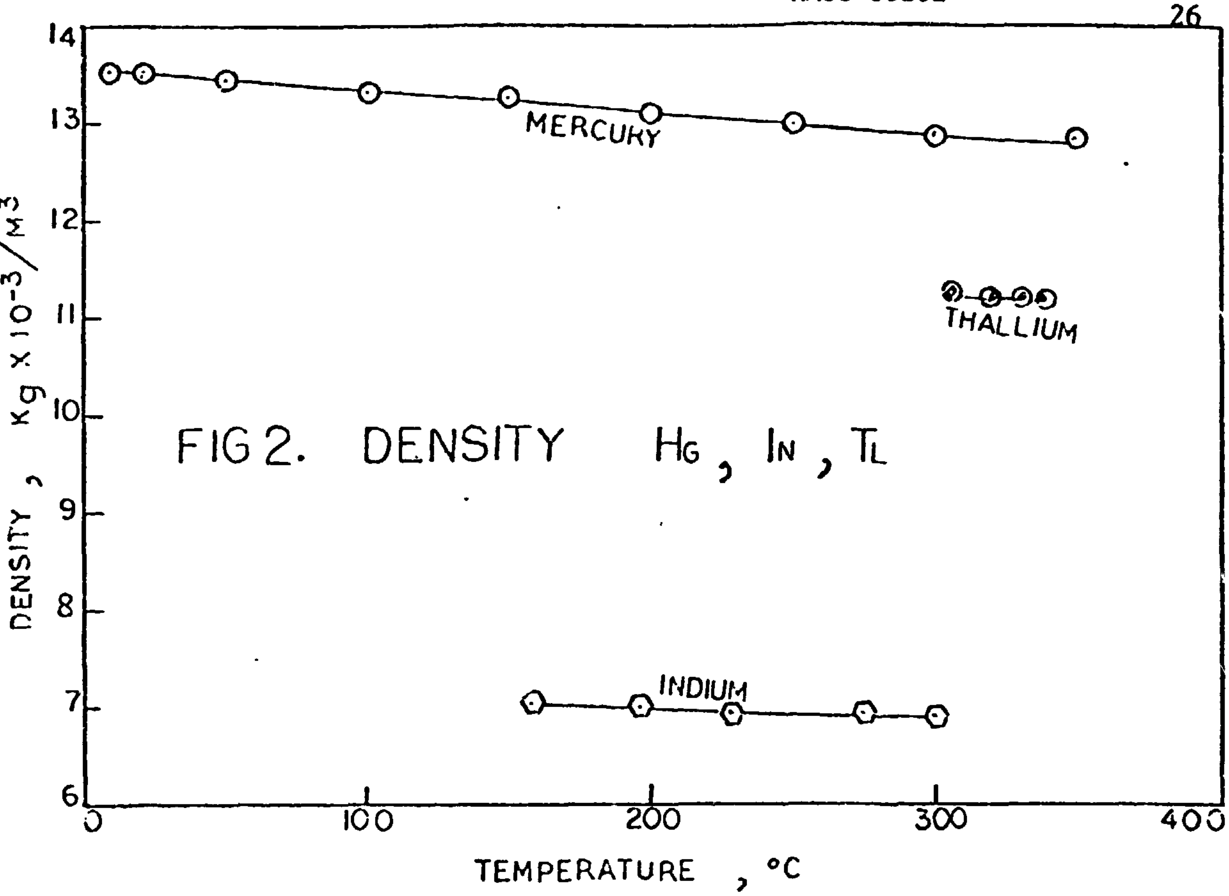


FIG 2. DENSITY HG, IN, TL
MERCURY
THALLIUM
INDIUM
DENSITY, Kg X 10-3/M3
TEMPERATURE, °C
6
7
8
9
10
11
12
13
14
0
100
200
300
400

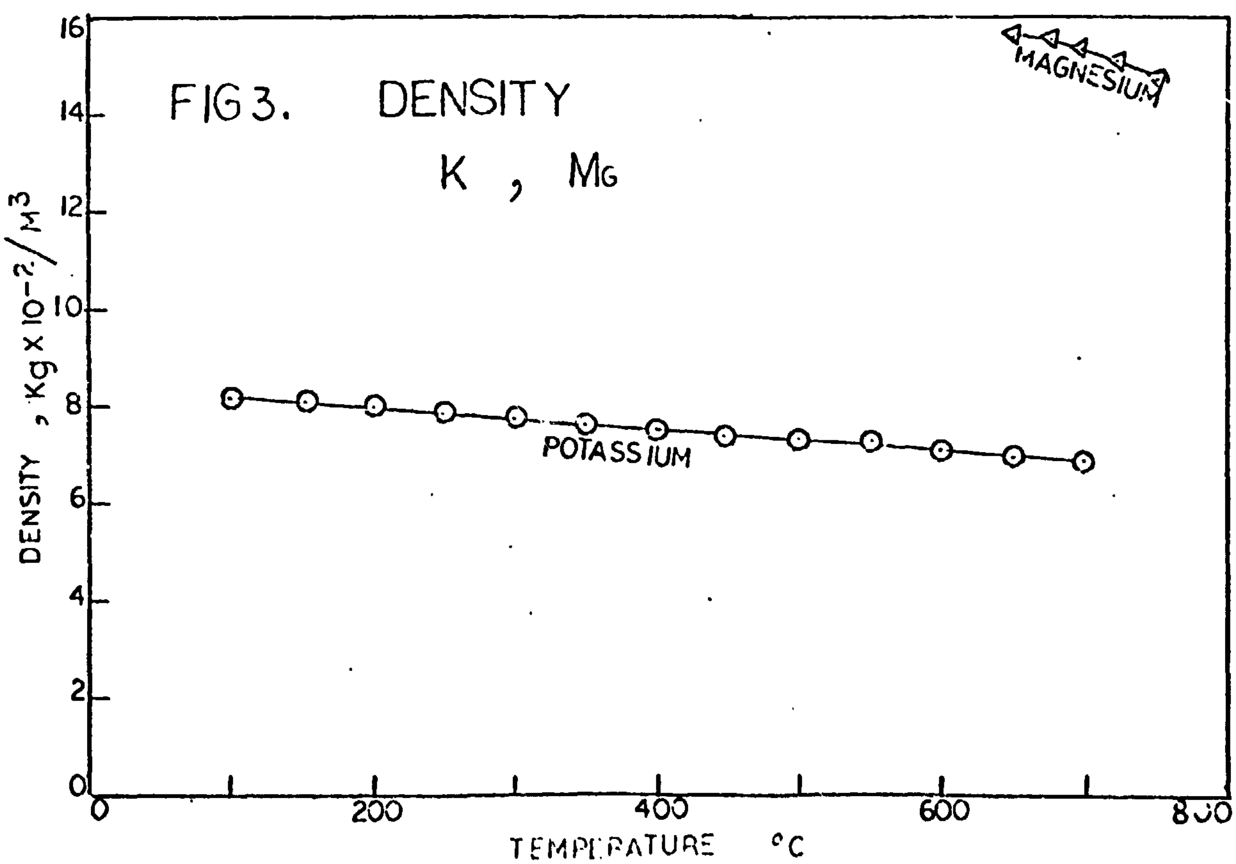


FIG 3. DENSITY
K, MG
MAGNESIUM
POTASSIUM
DENSITY, Kg X 10-?/M3
TEMPERATURE °C
0
2
4
6
8
10
12
14
16
0
200
400
600
800

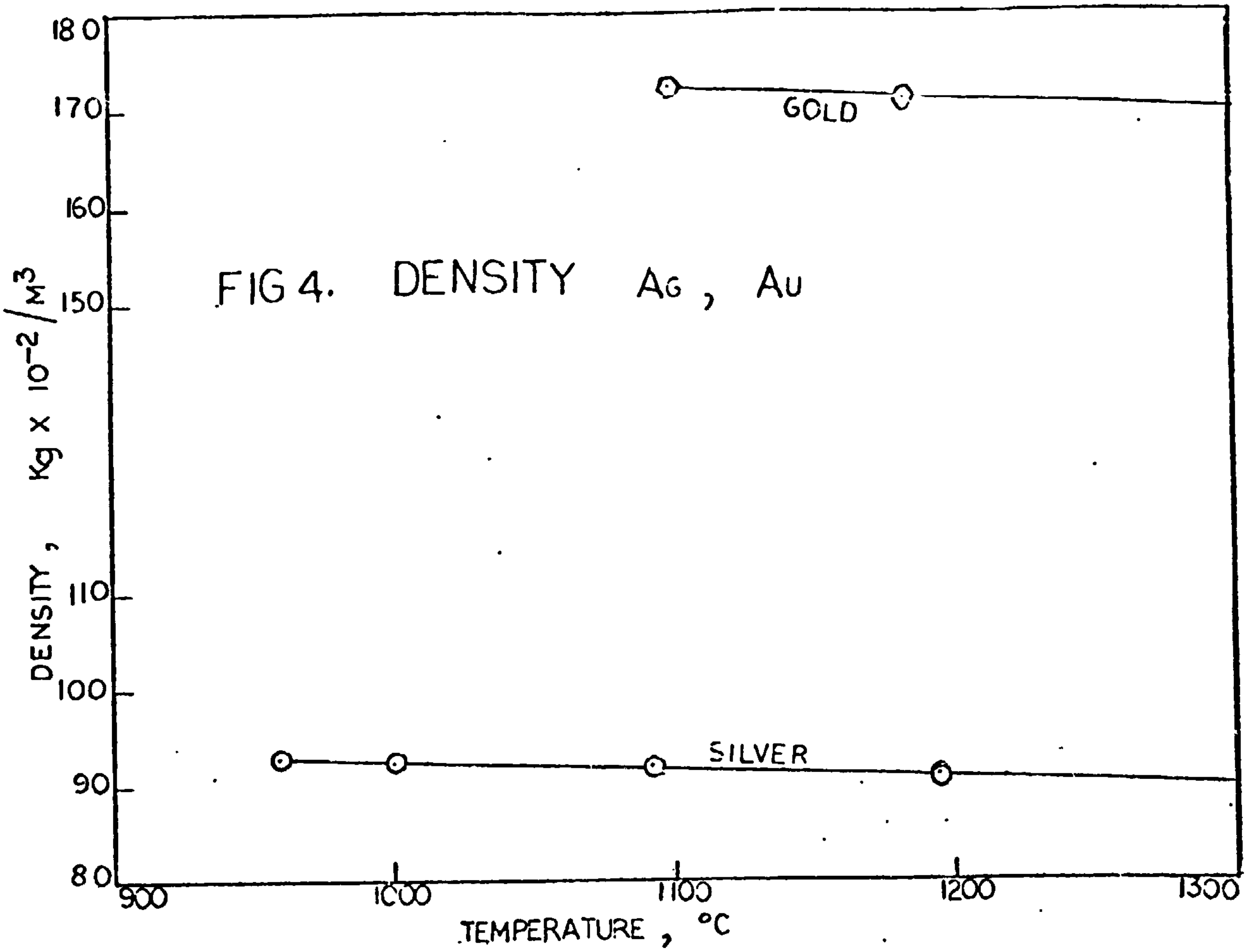


FIG 4. DENSITY Ag , Au

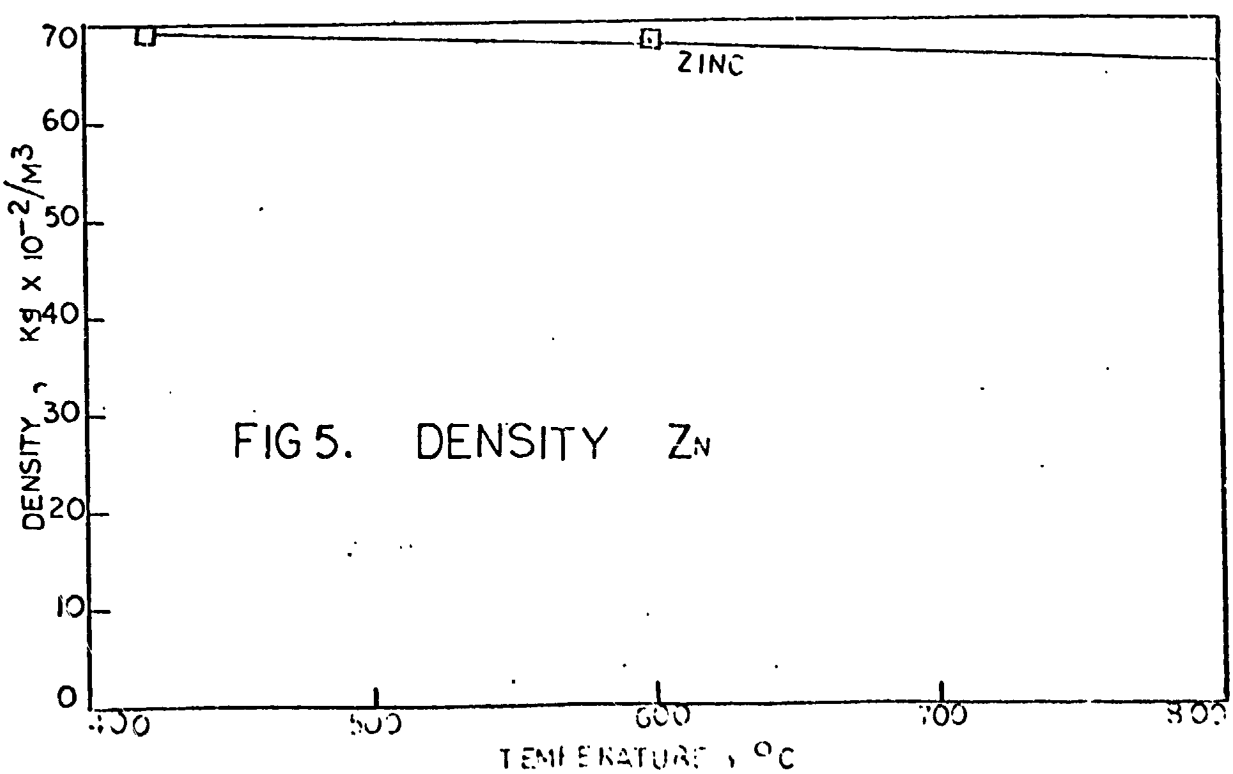


FIG 5. DENSITY Zn

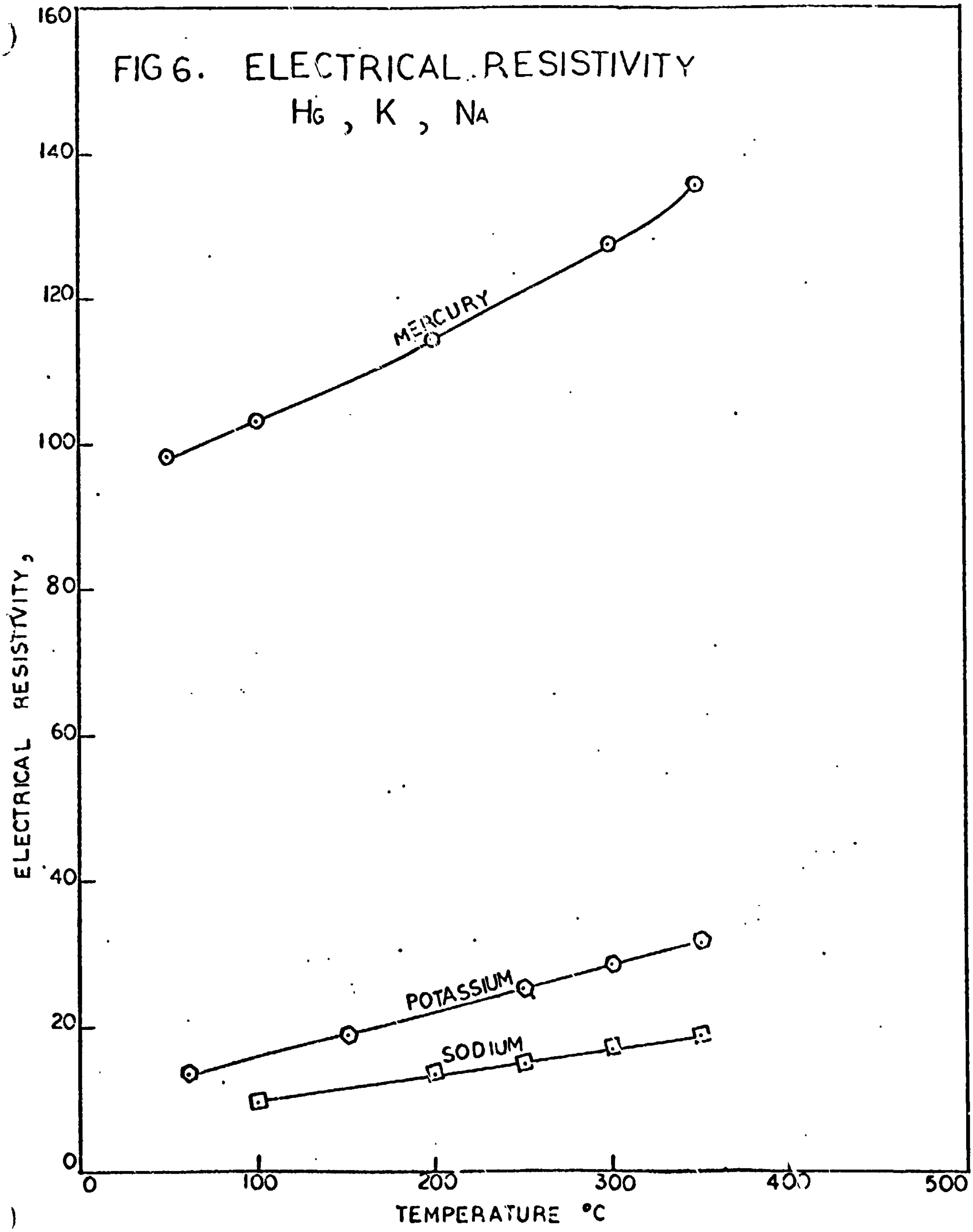


FIG 6. ELECTRICAL RESISTIVITY
HG, K, NA
MERCURY
POTASSIUM
SODIUM
ELECTRICAL RESISTIVITY,
TEMPERATURE °C
0
20
40
60
80
100
120
140
160
0
100
200
300
400
500

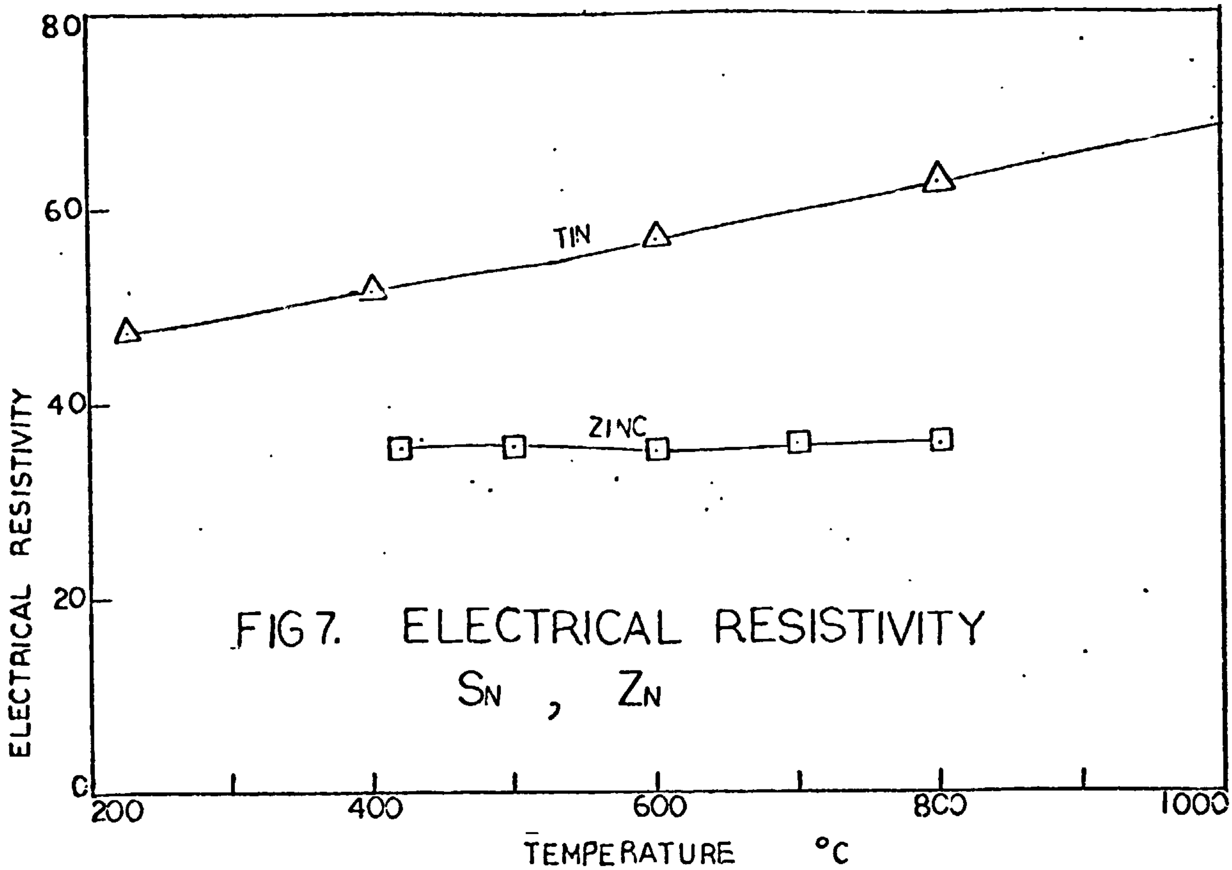


FIG 7. ELECTRICAL RESISTIVITY
Sn, Zn

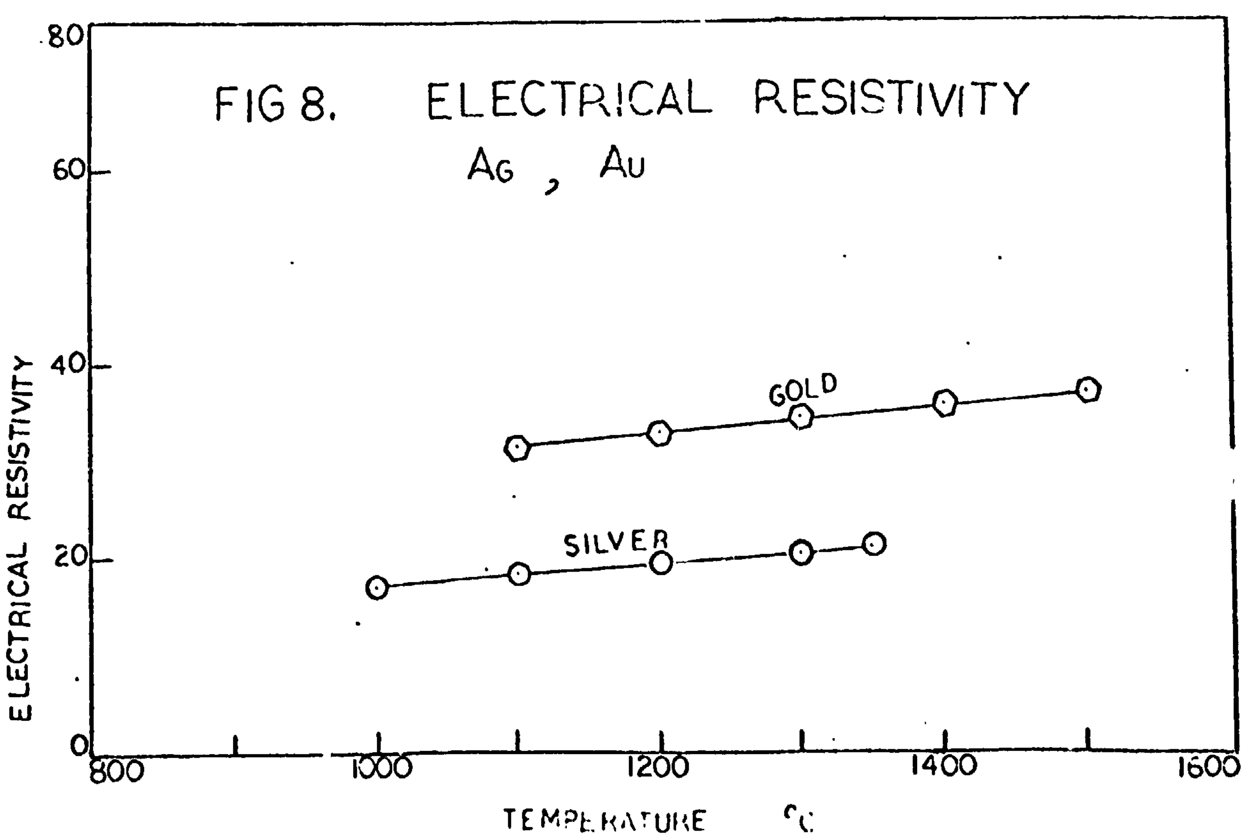


FIG 8. ELECTRICAL RESISTIVITY
Ag, Au

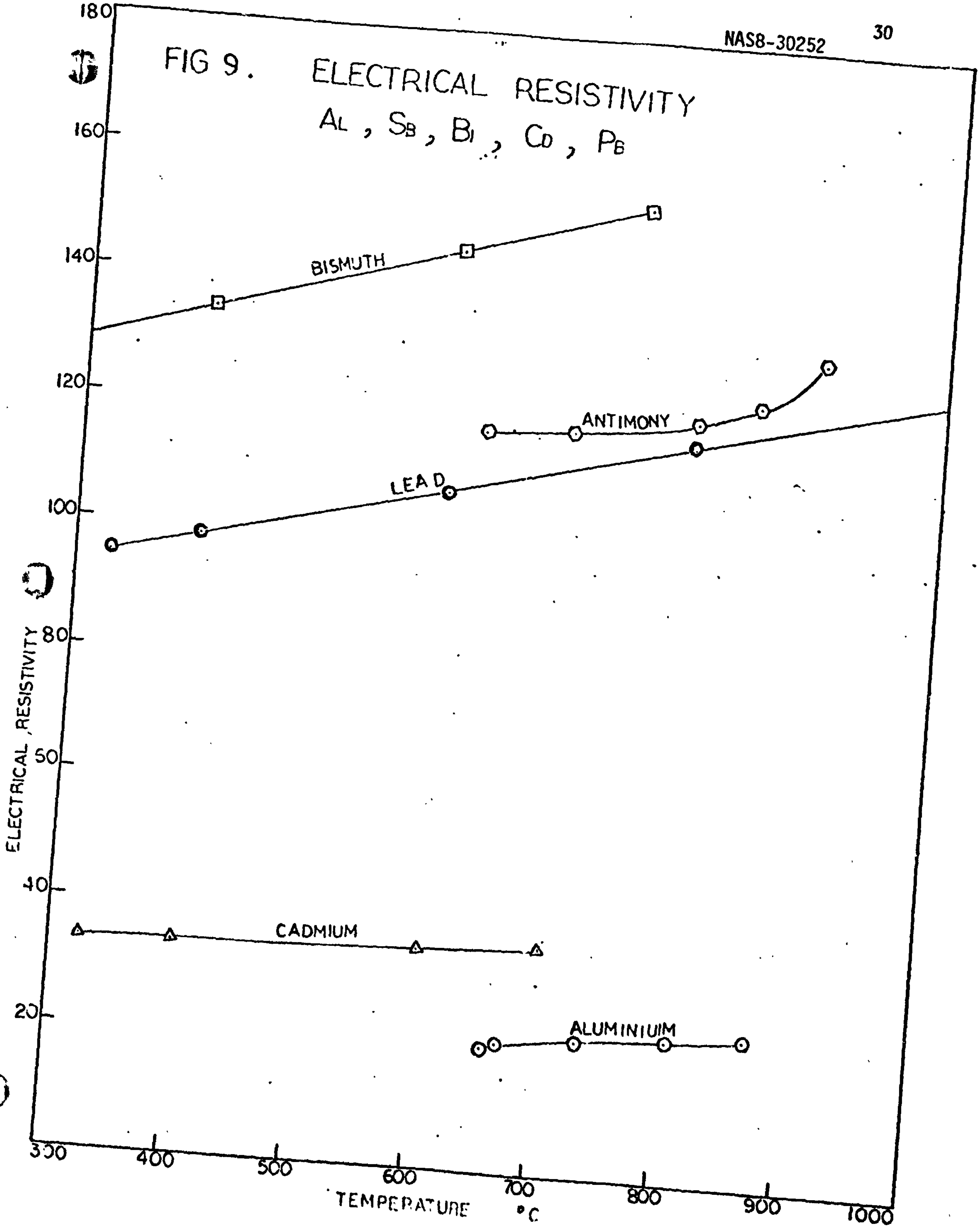


FIG 9. ELECTRICAL RESISTIVITY
AL , SB , BI , CD , PB
BISMUTH
ANTIMONY
LEAD
CADMIUM
ALUMINIUIM
ELECTRICAL ,RESISTIVITY
TEMPERATURE °C
180
160
140
120
100
80
50
40
20
300
400
500
600
700
800
900
1000

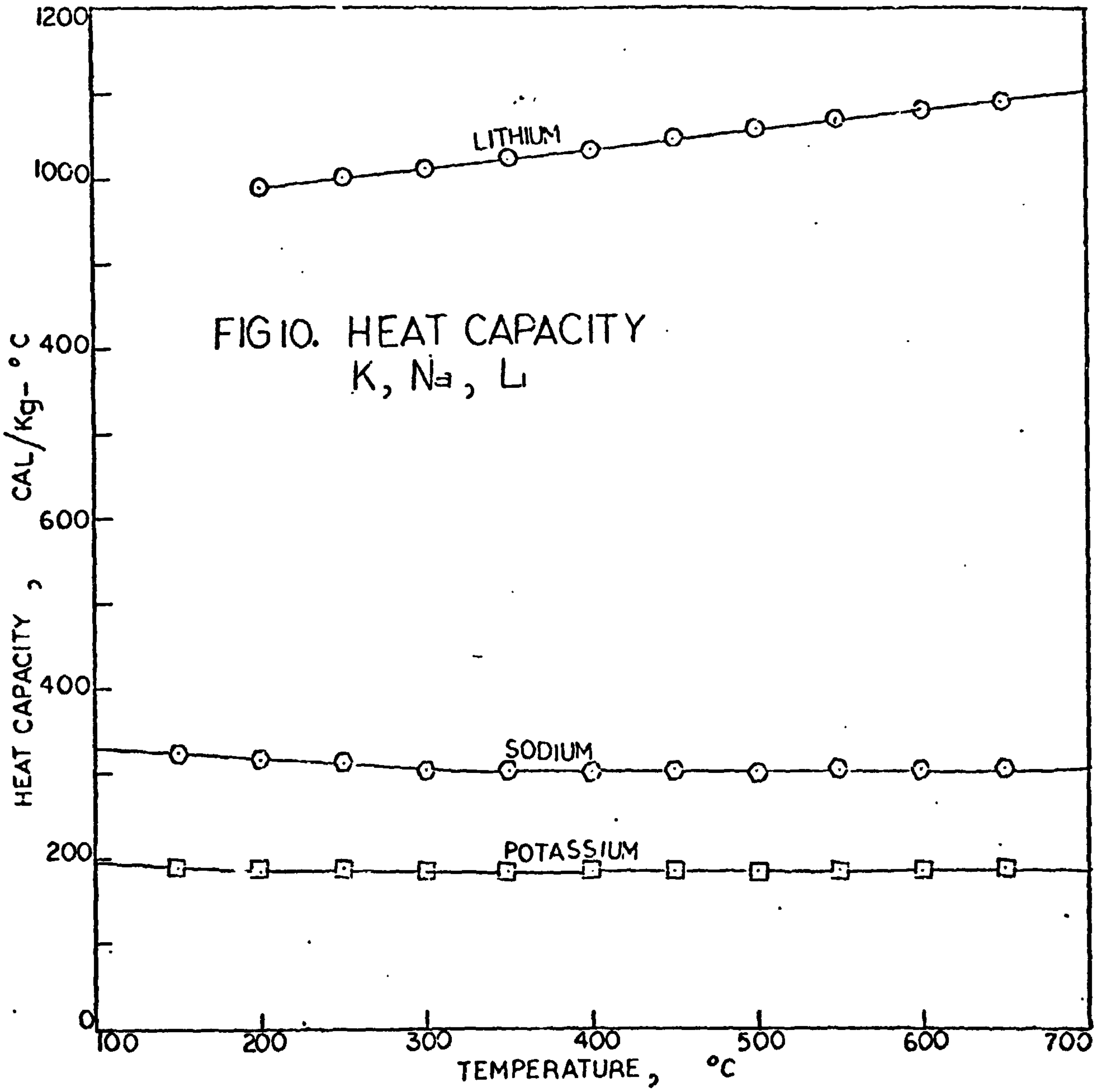
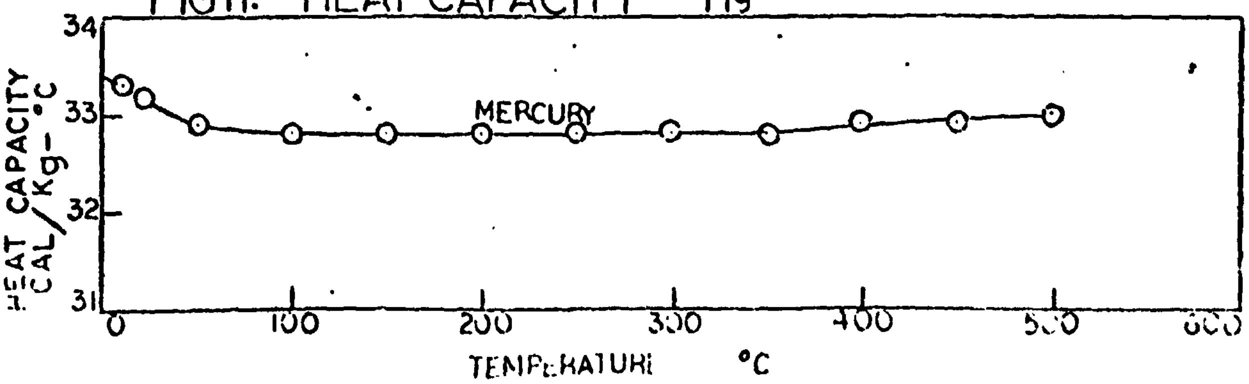


FIG 10. HEAT CAPACITY
K, Na, Li

FIG 11. HEAT CAPACITY Hg



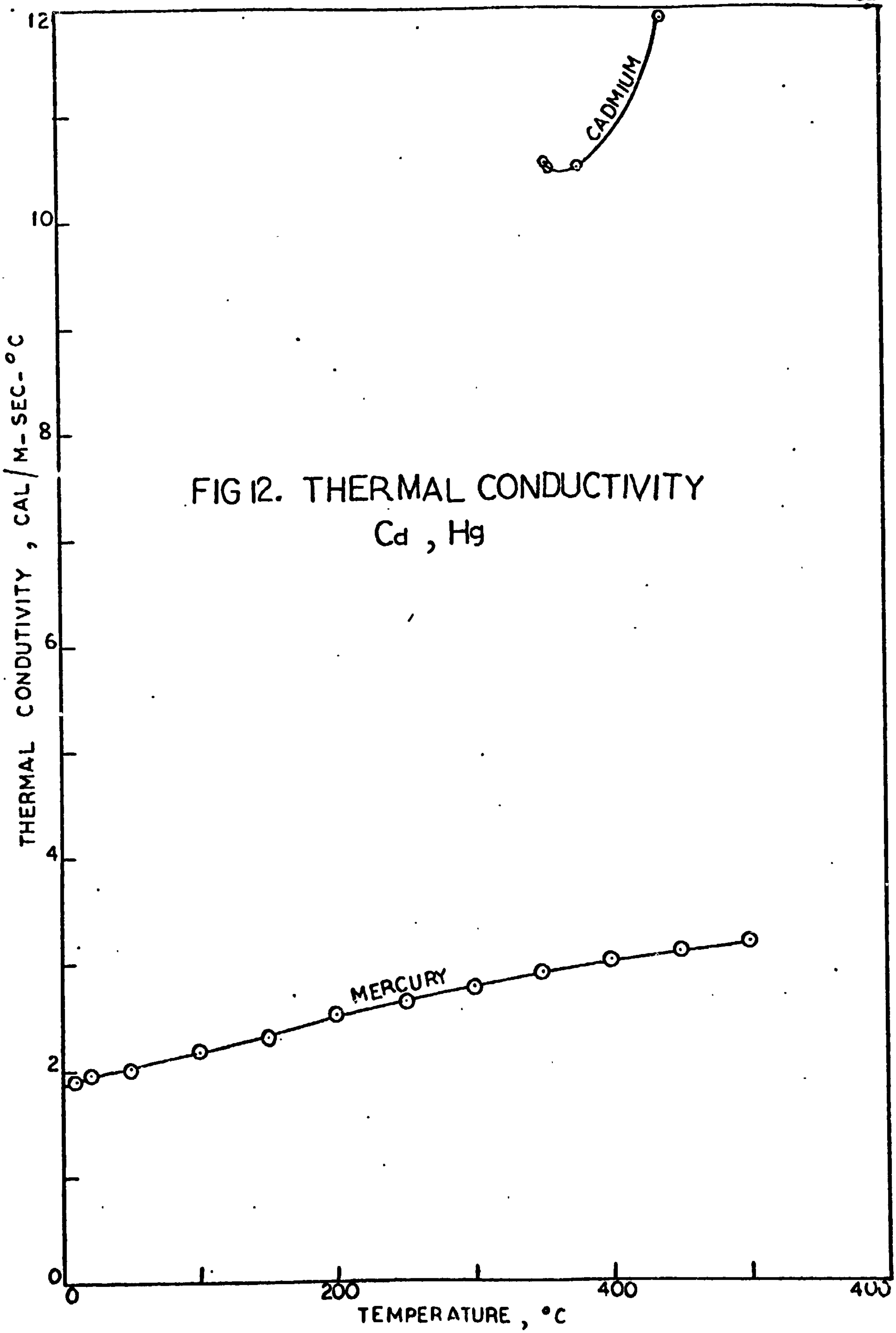


FIG 12. THERMAL CONDUCTIVITY
Cd , Hg
CADMIUM
MERCURY
THERMAL CONDUTIVITY , CAL/M-SEC-°C
TEMPERATURE , °C
0
2
4
6
8
10
12
0
200
400
400

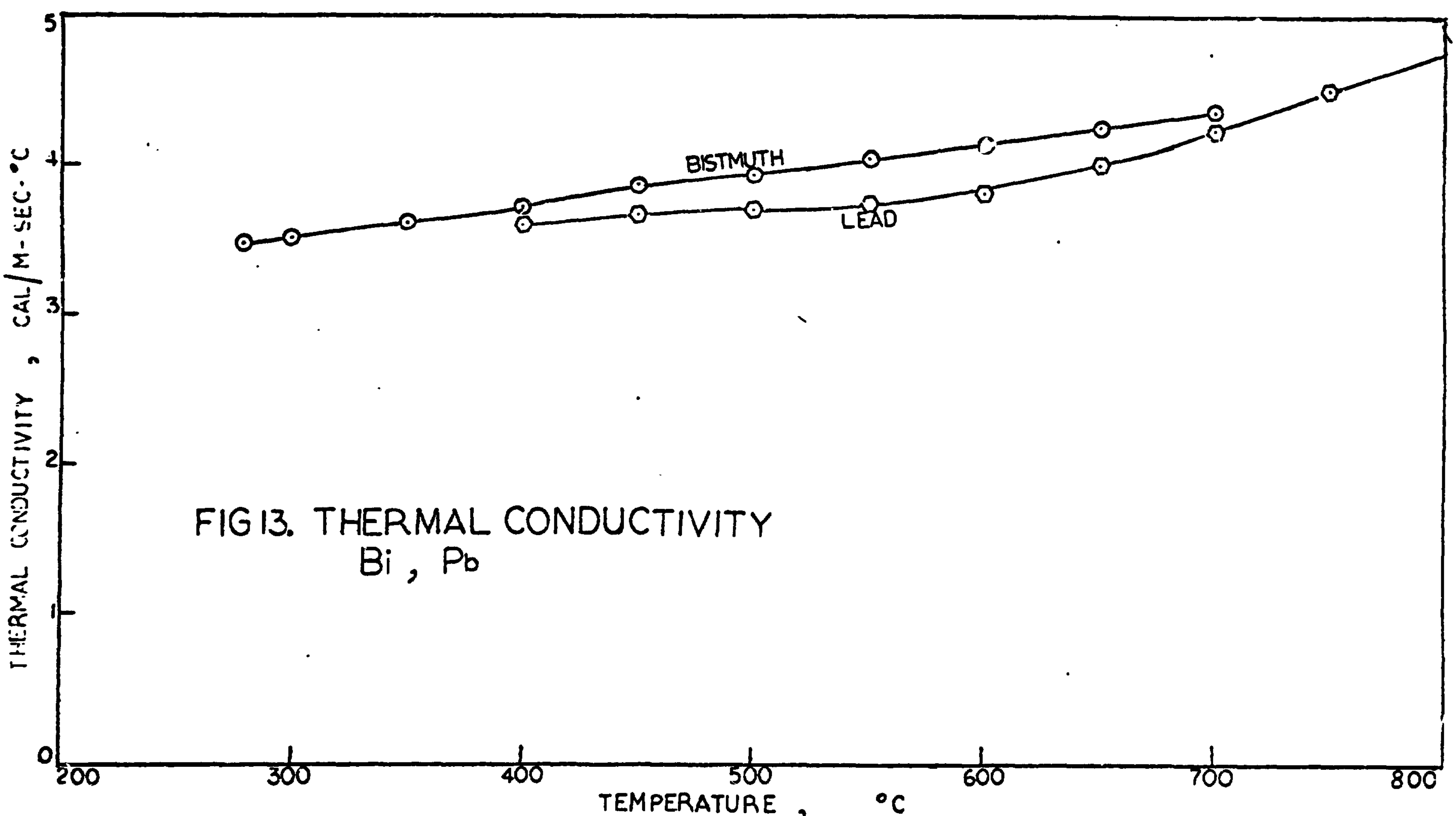


FIG 13. THERMAL CONDUCTIVITY
Bi , Pb

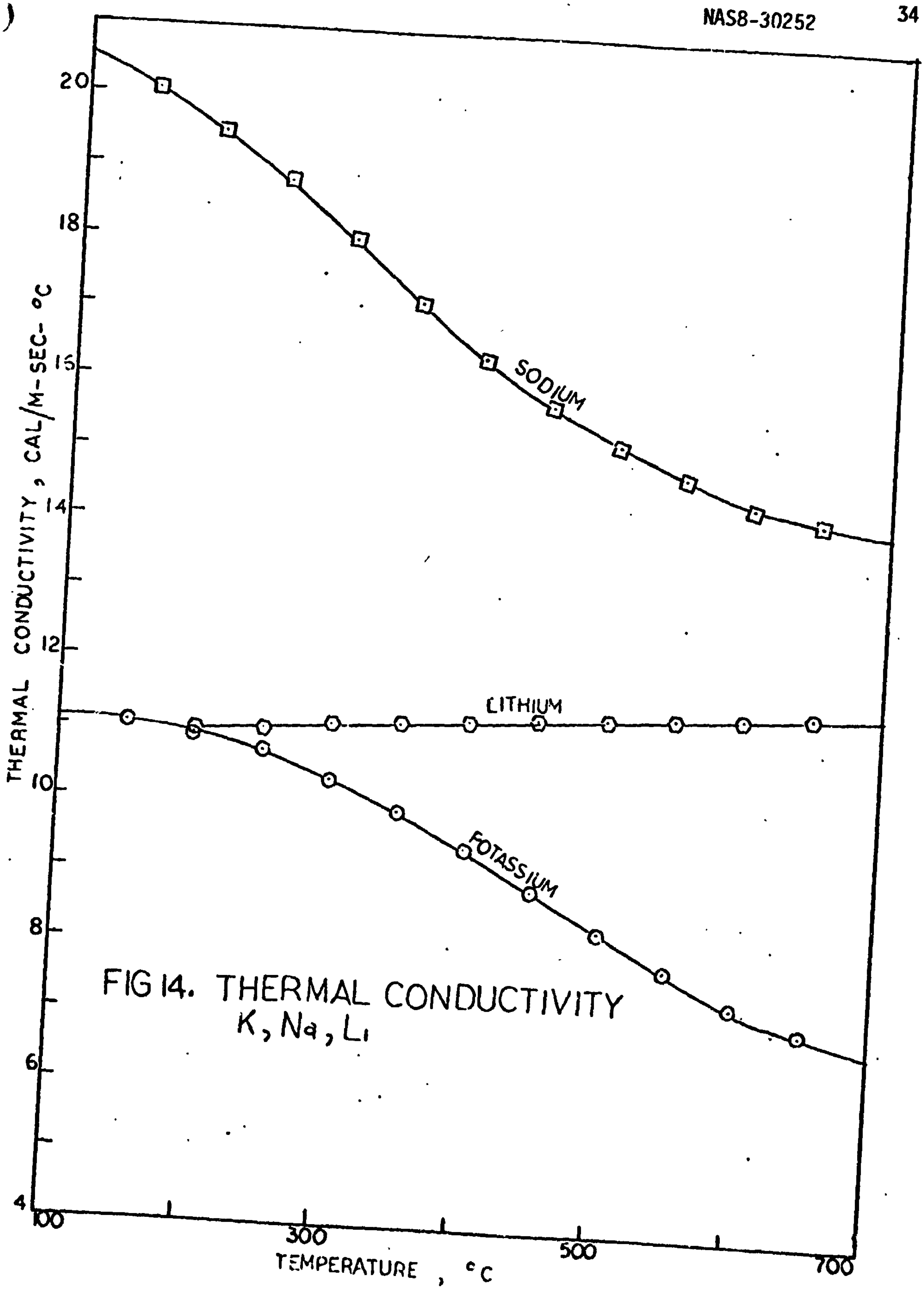


FIG 14. THERMAL CONDUCTIVITY K, Na, Li

SECTION II

HEAT TRANSFER CORRELATIONS IN LIQUID METALS

When a bulk of liquid metal is in contact with a solid surface heat transmission may occur by combined conduction-convection mechanism. An example of this is the transfer of heat between a liquid metal flowing through a tube in forced convection and the inner surface of the tube. In cases of laminar flow of liquid metals through tubes or natural convection around tubes, the heat-transfer coefficient can be predicted with reasonable assurance using the same relationships which apply to other types of fluids. However, in the case of turbulent forced convection inside tubes, the liquid-metal heat transfer cannot be predicted by the use of the equations of ordinary fluids. This is due to the extraordinarily high thermal conductivity of liquid metals which competes with the turbulence as a means of transporting heat. In addition, traces of scales on the wall may offer an important resistance to the over-all heat flow. In fact, contact resistance between the wall and a nonwetting liquid metal may reduce overall heat transfer by as much as one-half. The thermal resistance of the solid wall is also much more important than is usual in heat-transfer design.

In this section, forced-convection and natural-convection heat-transfer data are given. In addition to the symbols already defined in Section I, these other symbols are used:

D_e: Equiv. dia. = hydraulic dia. = (4 x cross-sectional area for flow)/(wetted perimeter), m

D_i: Inside tube diameter, m

D_o: Outside tube diameter, m

G = vd = mass velocity, Kg/(m^2-sec)

h : Heat-transfer coefficient, Cal/(m^2-sec-°C)

v : Flow velocity, m/sec

μ : Viscosity, Kg/(m-sec)

A. Forced-Covection Heat Transfer

1. Flow Inside Tubes. References 7, 31, and 32 agree that for values of (D_iGC_p/K) above 100 in liquid metals inside tubes, the heat-transfer correlation is given by Equation 1.

$$hD_i/K = 7 + 0.025(D_iGC_p/K)^{0.8}, \quad hD_i/K > 100 \qquad (1)$$

Refs. 31 and 33, give, from experimental data,

$$hD_i/K = 5 + 0.016(D_iGC_p/K)^{0.8} \quad 200 \le D_iGC_p/K \le 10{,}000 \tag{2}$$

The data given by other investigators fall within ±20% of Eq. 2, but are in general lower than values predicted by Eq. 1. Refs. 31 and 33 also give, from experimental data, Eq. 3.

$$hD_i/K = 1.7(D_iGC_p/K)^{1/3} - 3.9 \quad 20 \le D_iGC_p/K \le 200 \tag{3}$$

However, theory predicts a constant $hD_i/K = 4.37$ in the range covered by Eq. 3. Eqs. 1 and 2 may be used for turbulent flow of liquid metals inside tubes. Eq. 3 may be used for laminar and transition flow of liquid metals inside tubes in forced convection.

2. Flow Outside and Parallel With A Bundle of Tubes. For this kind of flow, Ref. 34 gives Eq. 4.

$$hD_e/K = 7.0 + 0.027(D_eGC_p/K)^{0.8}(p'/D_o)^{0.27} + 3.8(p'/D_o)^{1.52} \tag{4}$$

$$10 \le D_eGC_p/K \le 100{,}000; \ 1.375 \le p'/D_o \le 10$$

where
D_e = equiv. outside dia. of all the tubes
D_o = outside diameter of the individual tube
p' = pitch or spacing between tubes

3. Flow On The Shell Side Of Heat Exchangers. Ref. 7 gives for this case Eq. 5,

$$hD_o/K = 0.19(D_e)^{0.6}(D_oG_e/\mu)^{0.6}(C_p\mu/K)^{0.3} \tag{5}$$

where

D_e = equiv. dia. of the shell side in inches
G_e = mass velocity through the shell
D_o = outside diameter of tubes

Note that D_e must be in inches in Eq. 5, because that is how the equation was derived empirically. In baffled shells, G_e is the geometric mean of the mass velocity across the tubes and the mass velocity around the baffles.

For other noncircular ducts, calculate equivalent diameter, D_e and mass velocity, G_e, and substitute into the appropriate equation from among Eq. 1 to Eq. 5.

B. Natural-Convection Heat Transfer

Little experimental information on natural convection in liquid metals is available in the literature. Ref. 7 gives, for a horizontal circular cylinder, the following correlation:

$$hD/K = 0.53\ (C_p\mu/K)^2 \cdot Gr/(0.952 + C_p\mu/K)^{0.2} \qquad (6)$$

where

Gr = Grashof number = $gD^3\beta\Delta td^2/\mu^2$

Equation 6 may be used to evaluate heat-transfer coefficient, h, in natural-convection heat transfer for a liquid metal, particularly when there are no experimental data that are reliable.

SECTION III

DIFFUSION IN LIQUID GALLIUM-INDIUM SOLUTION

The objective of the experimental study was to determine the values of mass diffusivity (coefficient of diffusion) D when a liquid gallium-indium solution of known concentration was allowed to diffuse into essentially pure liquid gallium at various constant temperatures. The method, which employed diffusion through porous disks, gave only concentration average diffusion coefficient. However, since the diffusion constants of many non-alkali liquid metals do not depend significantly on concentration at low solute concentrations, the average diffusion constant determined by the porous disk method was approximately equal to the true diffusion coefficient.

THEORY

Diffusion is much faster in liquids than in solids; however, it is much slower in liquids than in gases. Liquid diffusion coefficients are of the order of magnitude of 10^{-5} cm^2/sec. At low concentrations, diffusion coefficients in liquid metals are almost independent of concentration.

Diffusion out of a homogeneous thin disk with plane parallel faces may be approximated by Fick's law of diffusion equation at constant temperature

$$\frac{\partial c}{\partial t} = D \frac{\partial^2 c}{\partial x^2} \tag{7}$$

where c is the concentration at time t and at a distance x from the center of the disk along the normal to the plane parallel faces. For a porous disk containing solution, Eq. (7) will still hold if one defines an effective cross-sectional area A, and an effective thickness 2L so that the integral over these dimensions of c(t) equals Q(t), the amount of solute contained in the frit at time t. If the diffusion constant D is assumed to be independent of concentration or understood to be an average integral diffusion constant over the concentration range involved, Eq. (7) can be readily solved to give

$$Q(t) = A \int_{-L}^{L} [c(x,t) - c_0]dx$$

$$= \frac{16}{\pi^2} LA(c_1 - c_0) \sum_{n=0}^{\infty} \frac{1}{(2n+1)^2} \exp[-Dt(2n + 1)^2\pi^2/4L^2] \tag{8}$$

where c_1 is the initial concentration in frit at time $t = 0$ and c_0 is the concentration in the solvent bath which is assumed to be constant. For time sufficiently long, Eq. (8) can be approximated by

$$Q(t) = \frac{16}{\pi^2} LA\,(c_1 - c_0)\,\exp(-D\pi^2 t/4L^2) \tag{9}$$

If $W(t)$ is the weight of the frit suspended in the solvent (gallium) bath at time t and W_S is the weight after equilibrium is reached, then

$$W - W_S = A \int_{-L}^{L} [\rho(x,t) - \rho_0]dx \tag{10}$$

where $\rho(x,t)$ is the density of gallium-indium solution in the frit at point x and time t and ρ_0 is the density of the liquid gallium in the solvent bath. If the density of a solution as a function of concentration can be represented by a linear function $\rho(c) = \rho(0) + kc$, where $\rho(0)$ is the density of the solvent used to make the solution, then one obtains

$$W - W_S = Ak \int_{-L}^{L} [c(x,t) - c_0]dx = kQ(t) \tag{11}$$

Substituting Eq. (11) into Eq. (9) and rearranging, one finds that

$$\ln(W-W_S) = -D\pi^2 t/4L^2 + \ln[16AkL(c_1-c_0)/\pi^2] \tag{12}$$

The functional form of Eq. (12) is

$$\ln(W - W_S) = -\alpha D + \ln B \tag{13}$$

where α and B are constants that should be determined experimentally.

According to Eq. (13) a plot of $\ln(W-W_S)$ vs. t should give a straight line of slope $-\alpha D$ where α is an apparatus constant. A caliberation of the frit with a solution of known diffusion properties is required to evaluate α. Once α is known, the diffusion constant D may be evaluated. By changing the temperature of the bath, values of D at various temperatures may be determined [1,2].

EQUIPMENT

The experimental setup used is shown in Fig. 15. A Fisher Scientific chainomatic analytical balance was mounted on a wooden table over a "Blue-M Magniwhirl" water bath in which temperature was controlled automatically to an accuracy of ±0.1°C. We modified the balance by drilling a large hole in the base directly below the left pan and also a large hole in the table directly below that in the balance. A thin tough nylon string was tied on the left pan to form a loop below the pan. Then a thin wire hook was suspended from the loop and passed freely through the holes. This allowed the porous disk to hang by a nylon string unhampered from the left balance pan into a solvent bath in the thermostat. Two 30 ml-capacity glass beakers were suspended in the thermostat which contained water. These beakers acted as containers for the gallium-indium solution and the gallium liquid solvent respectively.

The gallium-indium solution was prepared by first melting about 150 grams of gallium in the beaker at about 80°C and then adding about 20 grams of indium in small chunks until the indium was dissolved completely. The solution was thus about 11.92% indium by weight. Another 150 grams of gallium was melted in the second beaker to form the pure gallium solvent bath. The gallium was from a batch of 300 gm Gallium grade A1 produced by the Johnson Matthey Chemical Ltd of London, England and vended as 99.999% pure by United Mineral & Chemical Corp., New York, N.Y. in 12 capsules containing 25-gm gallium ingots each. Indium was also supplied by the same dealer and manufacturer as supplied gallium. It came in the same grade of purity as gallium. Four capsules containing 50 gm ± 2 gm each of indium were purchased.

Ten unglazed micro-porous filter plates 7.62 cm dia. (3 in.), 0.45 cm thick (3/16 in.) and grade 10 porosity were custom made for us by Selas Corporation of America, Dresher, Pennsylvania.

As a consequence of the high cost of gallium and indium and their limited availability, the porous disks were later cut up into smaller disks, each 2.065 cm dia. (13/16 in.). Also it was discovered that the disks would not sink in the solutions but would float on them instead. Hence, a piece of brass tube was used as a sinker for the disks.

EXPERIMENTAL PROCEDURE

The disk, weighted down by the sinker, was soaked in the solution overnight for about 12 hours at the pre-selected temperature controlled by the water thermostat. The pure gallium liquid solvent was also left in the bath overnight at the same selected temperature. Care was taken to cover two beakers containing liquid metal to prevent contamination.

At the start of the experimental weighing, the frit and brass tube sinker were removed from the gallium-indium beaker, the brass tube was slid off up the string and the frit (disk) alone was suspended from the pan of the balance and weighed in air. After the weighing, the brass tube sinker was slipped on again and the disk was immersed for a pre-set time in the pure gallium beaker. A stop clock was used to time the intervals. Diffusion was allowed to progress initially for 30 sec, then 60 sec and later 120 sec, and still later for 30 minutes or 1 hour at a time before the disk was removed from the beaker and reweighed in air without the sinker. The process was repeated until the weight of the sinker became constant. Results of the weighing and the accompanying cumulative diffusion time are tabulated in Appendix B. By changing the temperature control on the water bath thermostat, we were able to measure diffusion constants at 40.5°C, 50.5°C, 70°C and 80°C.

Attempts to weigh the disks while they were immersed in liquid were made futile by oscillations that made the balance readings erratic and unreliable; hence, the decision was made to weigh the disks while they were not immersed in the liquid. Care was taken to shake off any liquids clinging on the outside of the disk. This was easy to do since the gallium-indium solution as well as liquid gallium could hardly wet the disk. The metals behaved almost like mercury in glass.

RESULTS

Only small amounts (milligrams) of liquid were absorbed by the disks. However, since the chainomatic balance was so sensitive that it could measure 0.05 m-gm, it was possible to detect small variations in weight. The results of the weighings have been tabulated in Appendix B, and graphed in Fig. 16 to Fig. 23. Experimental values of αD, α and D determined from this study have been summarized in Table 21. An average value for α was obtained by repeating the experiment at 25°C with a solution of potassium chloride in water of 1.25 molarity and using water as the solvent it diffused into. Using the values of αD from the slope of the $\ell n (W-W_S)$ vs. t graph and the known diffusion constant $D = 1.92 \times 10^{-5}$ cm^2/sec for $KC\ell$ solution of this molarity, we were able to determine average α as 507.38 cm^{-2}. A plot of $\ell n(D)$ vs. 1/T for the gallium-indium solution is given in Fig. 24, where T is °K.

Table 21. EXPERIMENTAL VALUES OF DIFFUSION COEFFICIENT (D)

(Ga-In solution of concentration 11.92% In by weight diffusing into liquid Ga 99.99% pure)

$\alpha = 507.38\ cm^{-2}$; $D = 8.563\times10^{-5}\exp(-\frac{1028}{RT})\ cm^2/sec$; $R = 1.987$ cal/gmol-°K

T =°K

Temperature °C	$10^3\ \alpha D\ Sec^{-1}$ Trial 1	Trial 2	Avg $10^3\ \alpha D\ Sec^{-1}$	$10^5 D$ cm^2/sec
40.5	8.372	8.346	8.346	1.645
50.5	8.778	8.798	8.788	1.732
70.0	9.621	9.617	9.620	1.896
80.0	10.041	9.945	9.993	1.970

DISCUSSION

Experimental values of diffusion coefficient in liquid gallium-indium solution are difficult to locate in the literature. However, the results of this study are of the order of magnitude that one would expect for liquids. The activation energy of 1028 cal/g-mol is close to what would be predicted from viscosity data for gallium.

The most troublesome point was the difficulty in finding an inert porous disk heavy enough to sink in liquid gallium or in the gallium-indium solution of density 7 gm/cm^3 approximately. Another difficulty was due to the fact that the amount of solution absorbed by the disk was very small. The solution had a very high surface tension and tended not to wet the disk. An oxide layer also tended to form. A small piece of paper tissue was used to wipe the oxide layer off. The paper did not get wet. This method of determination of diffusion constant works well and fast.

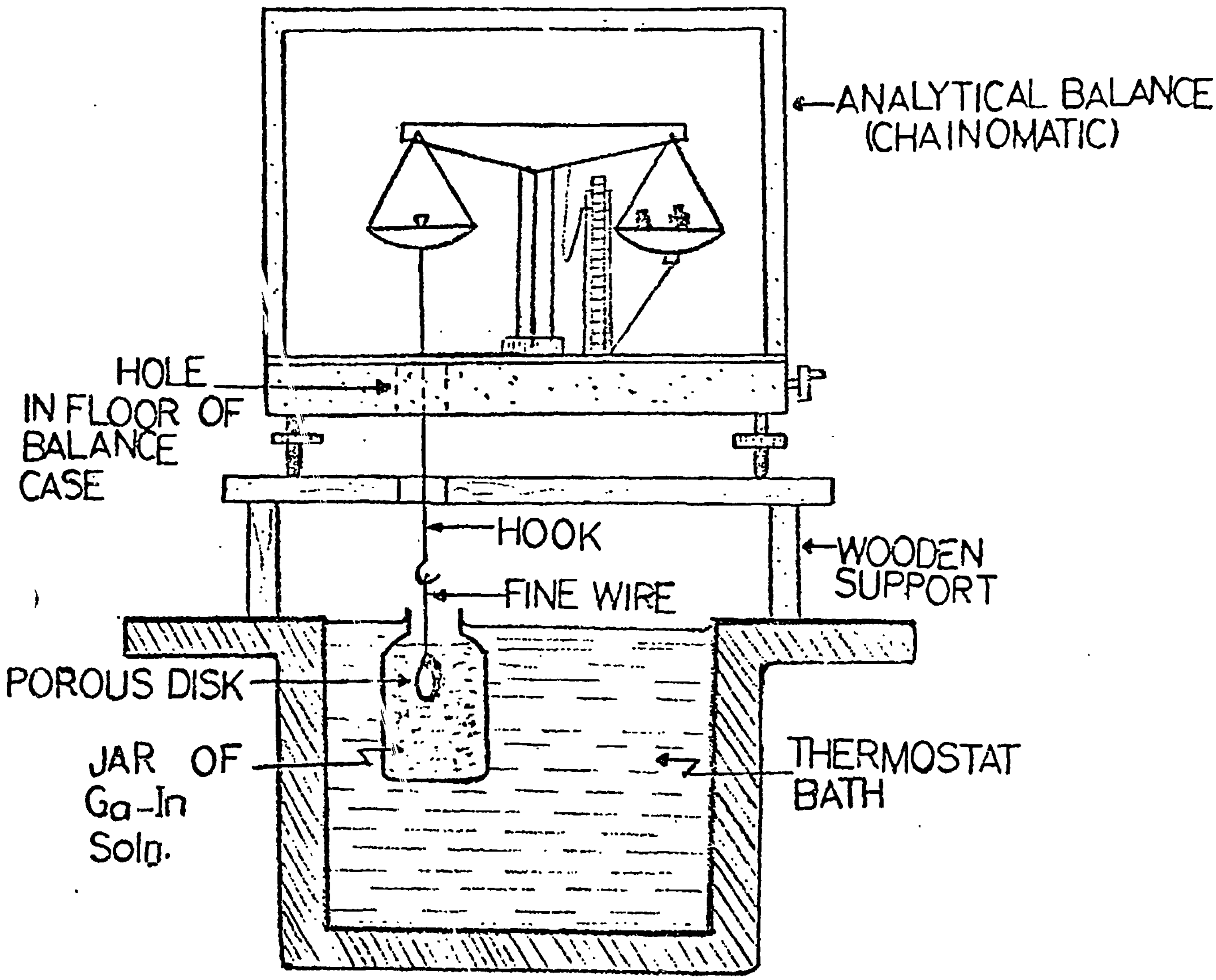


FIG. 15. DIFFUSION FROM A POROUS FRIT

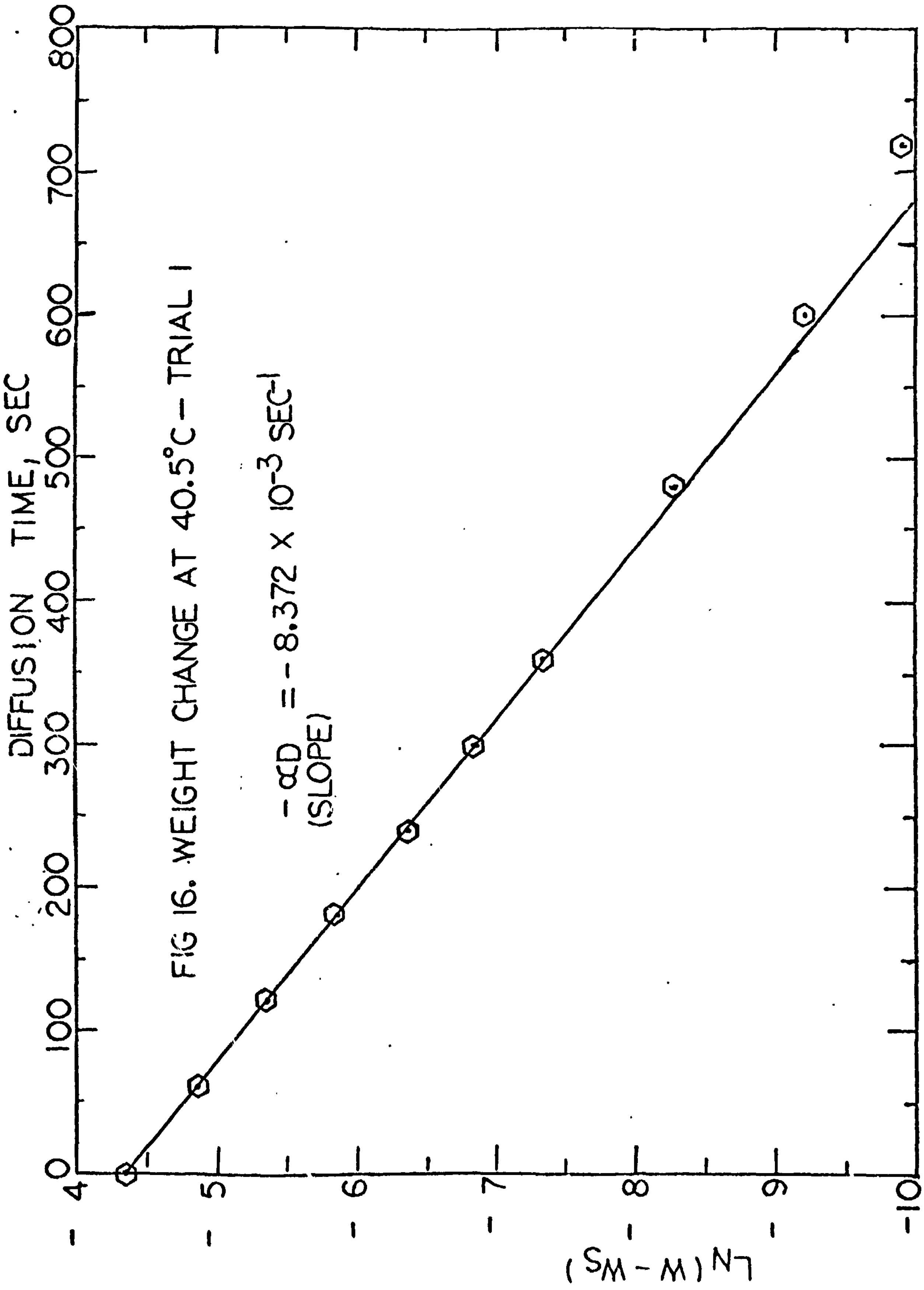


FIG 16. WEIGHT CHANGE AT 40.5°C — TRIAL I

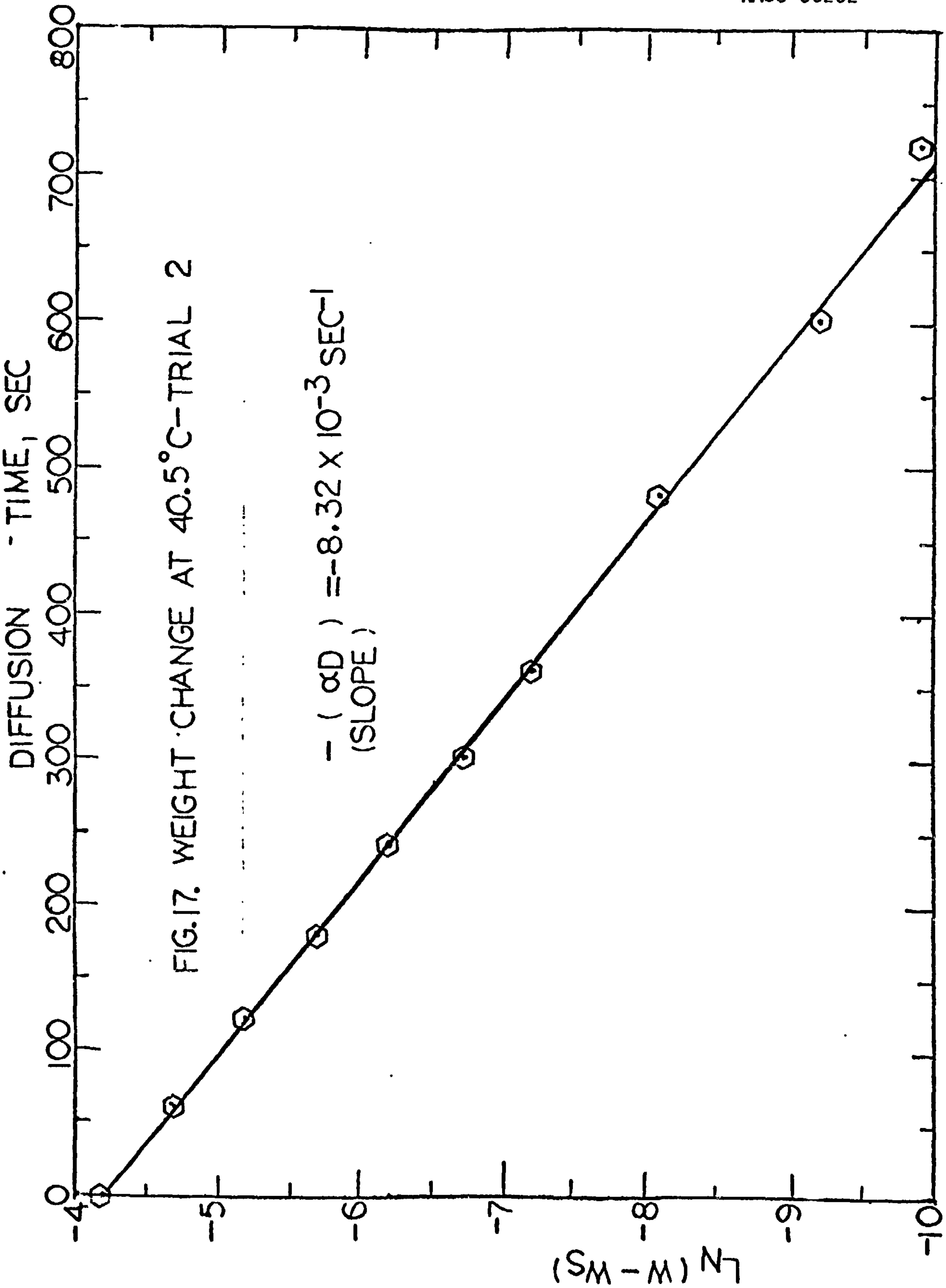


FIG. 17. WEIGHT CHANGE AT 40.5°C-TRIAL 2

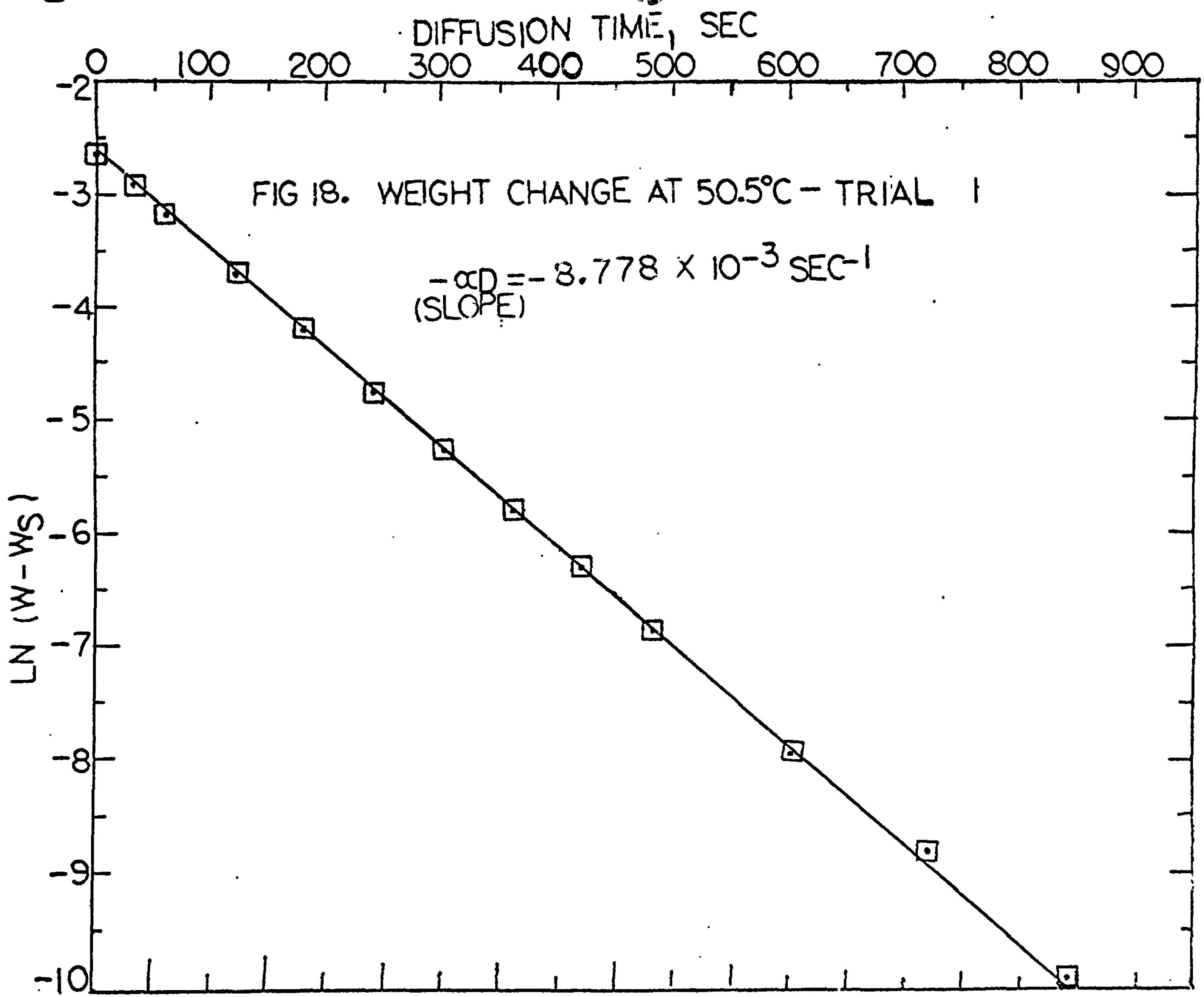


FIG 18. WEIGHT CHANGE AT 50.5°C – TRIAL I

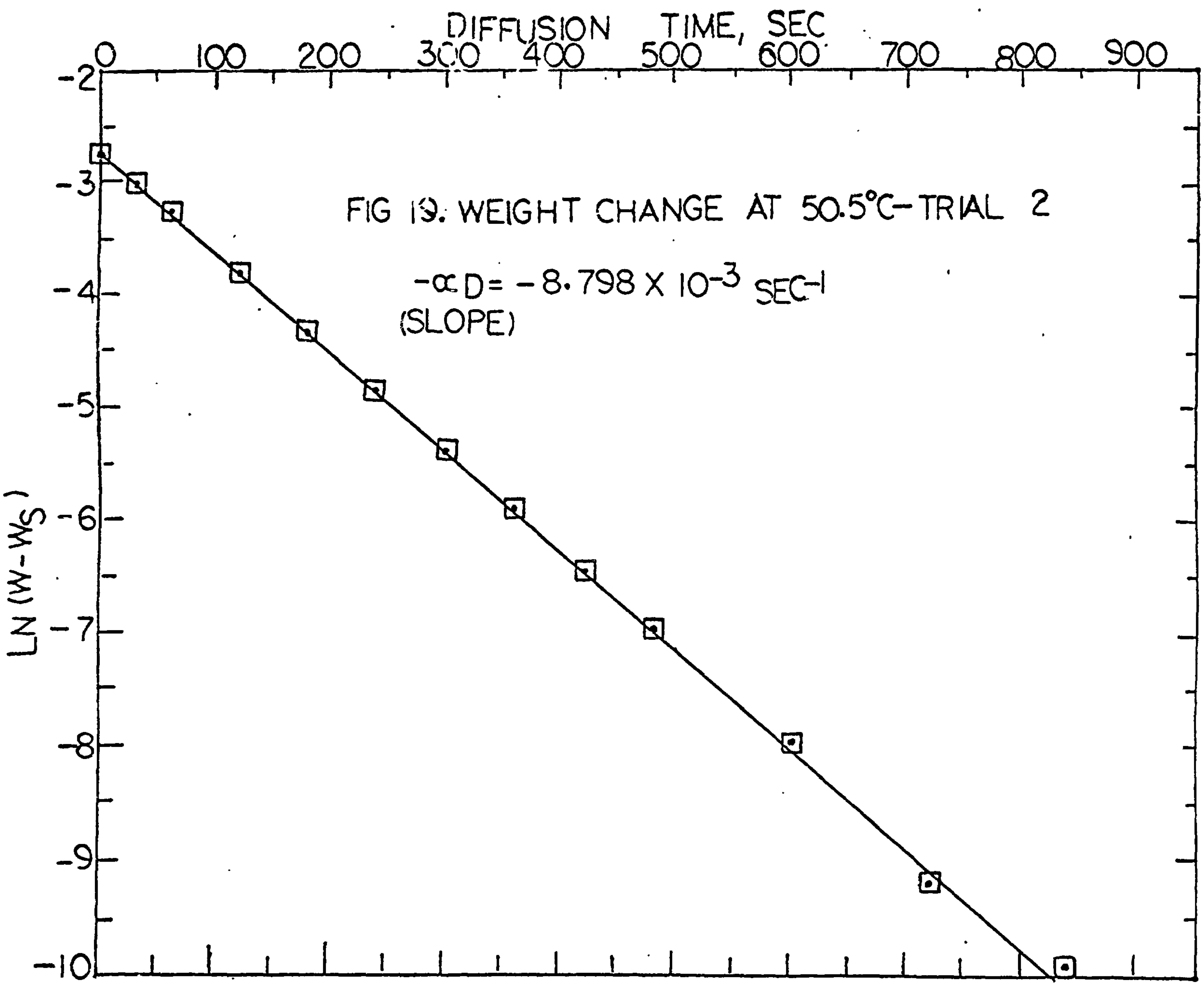


FIG 13. WEIGHT CHANGE AT 50.5°C–TRIAL 2

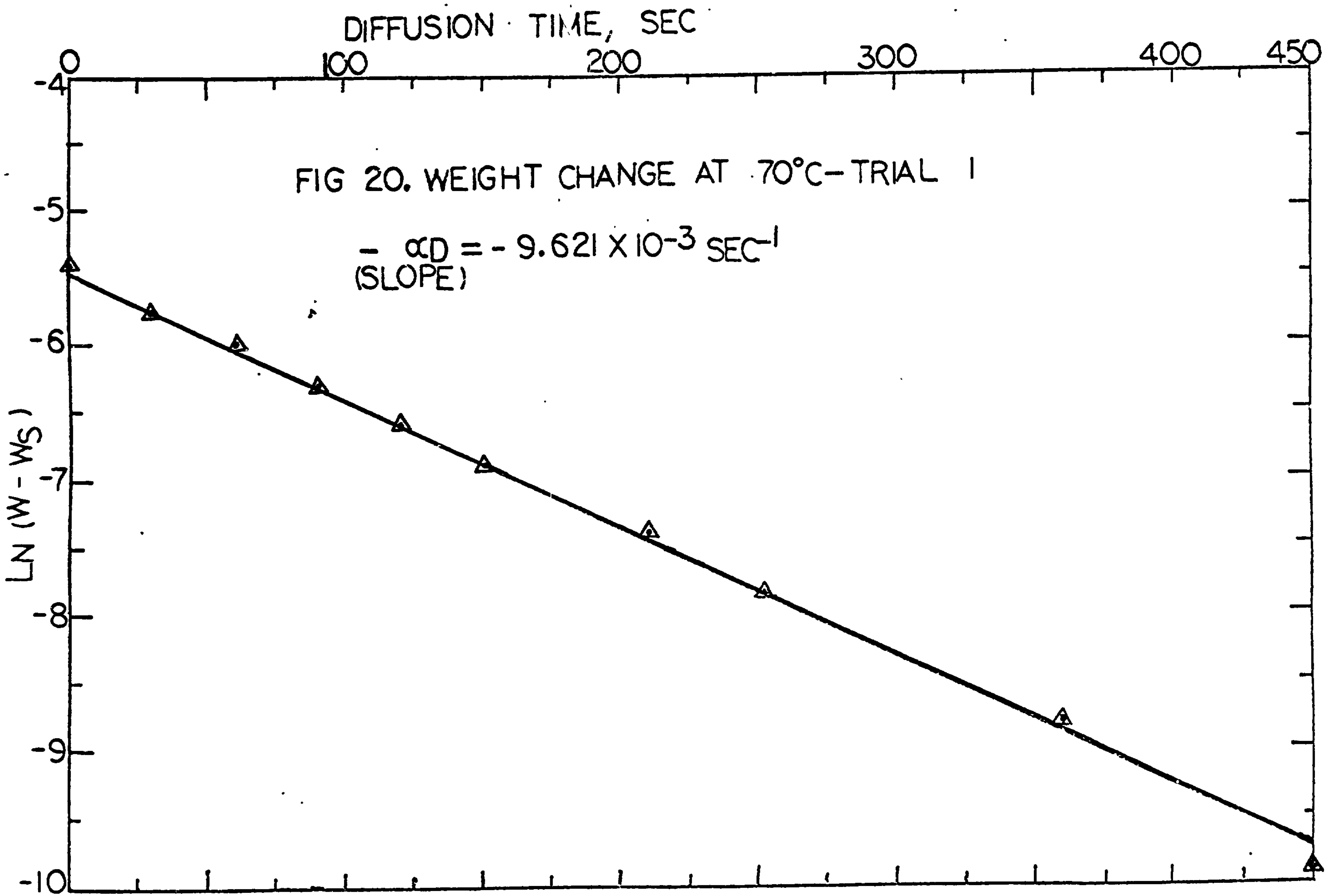


FIG 20. WEIGHT CHANGE AT 70°C–TRIAL 1

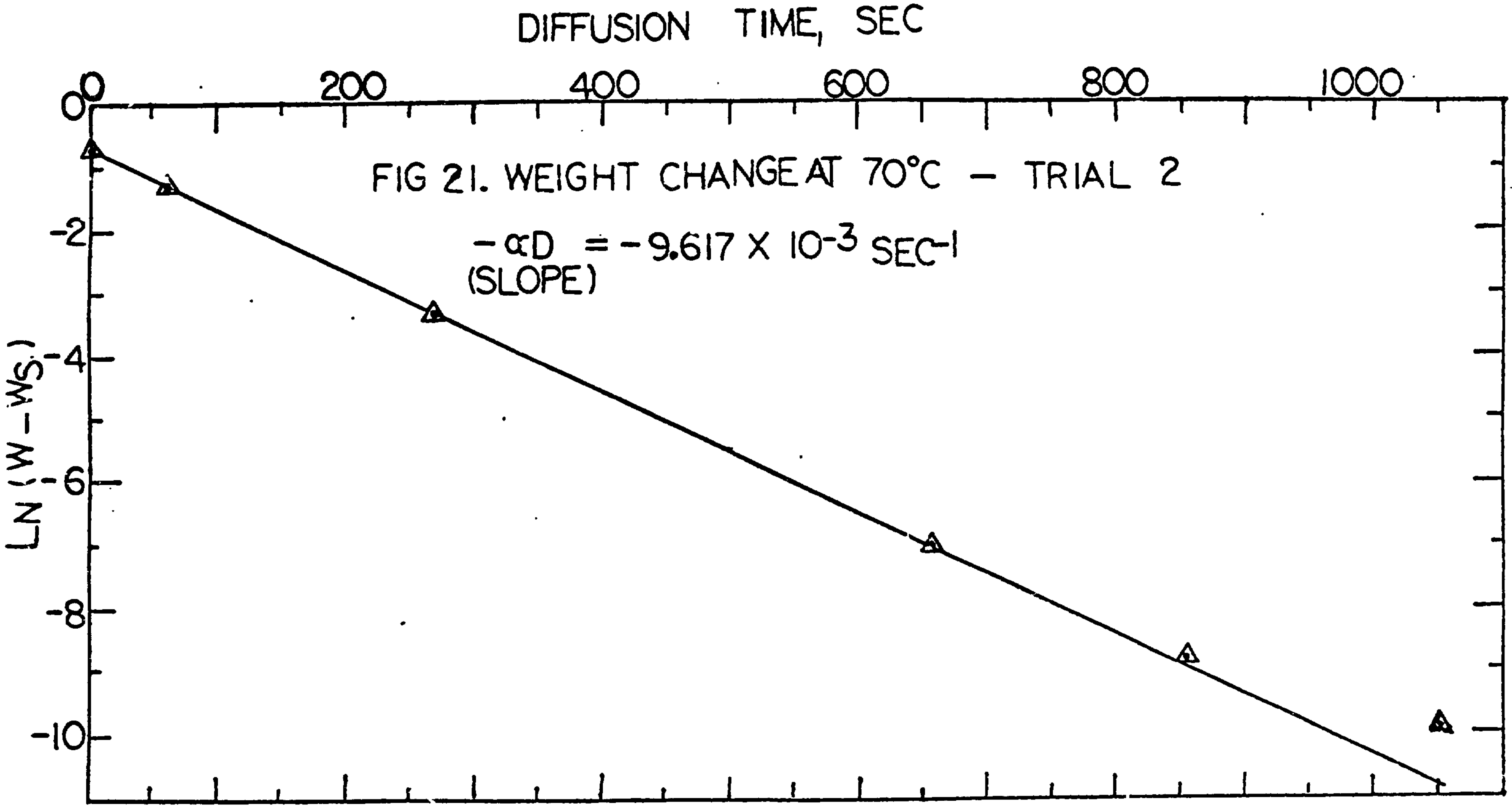


FIG 21. WEIGHT CHANGE AT 70°C — TRIAL 2

$-\alpha D = -9.617 \times 10^{-3}\ SEC^{-1}$
(SLOPE)

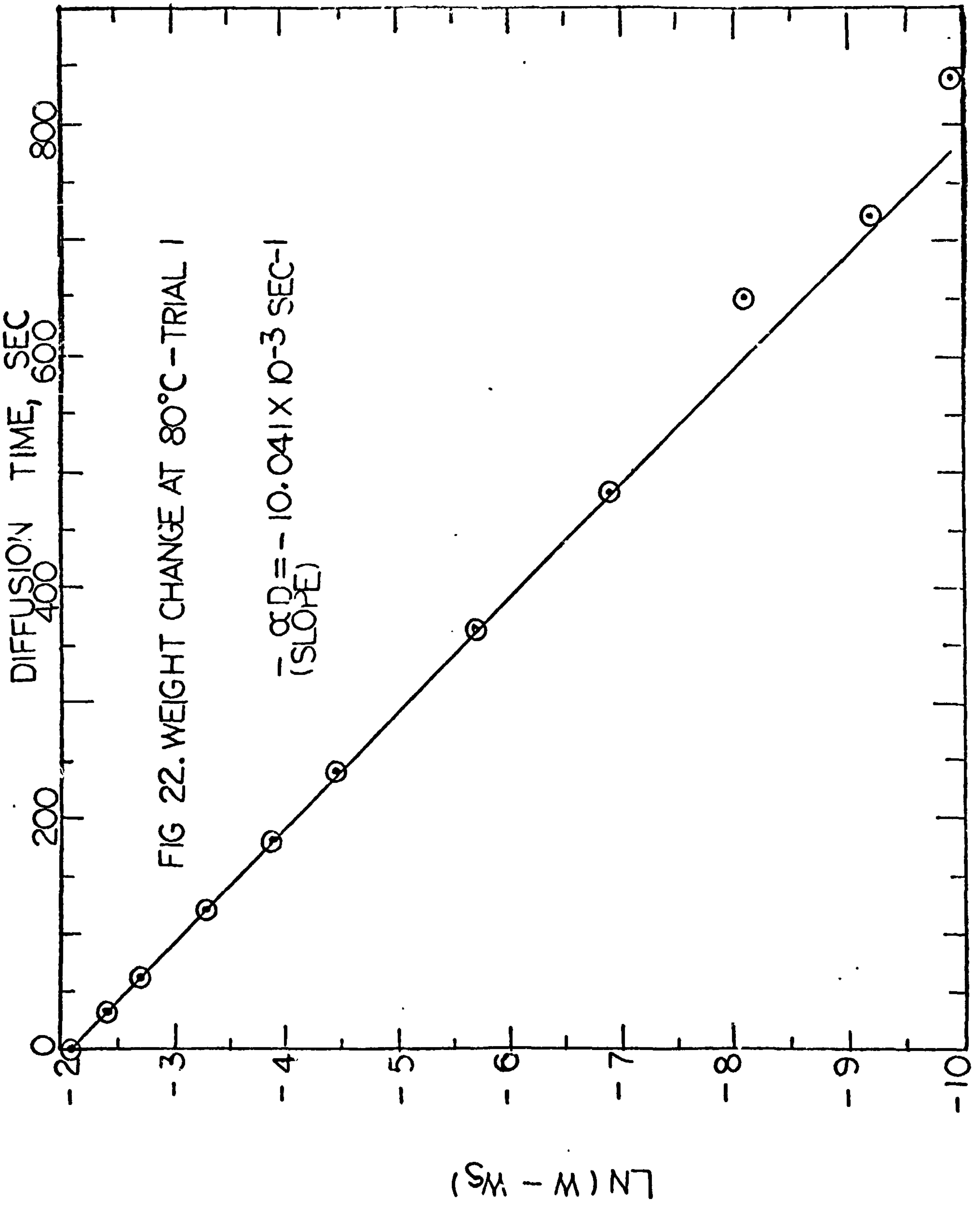


FIG 22. WEIGHT CHANGE AT 80°C – TRIAL I

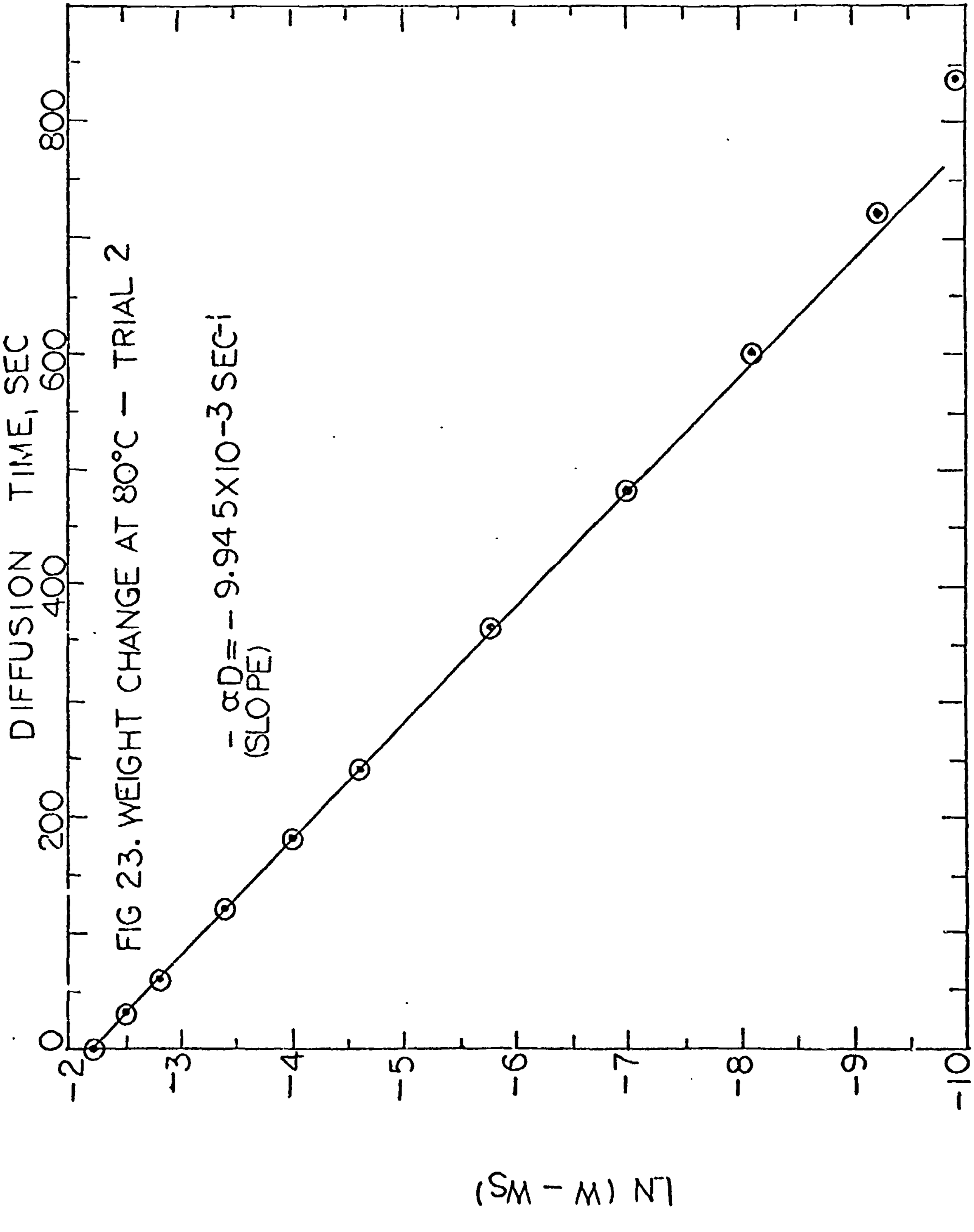


FIG 23. WEIGHT CHANGE AT 80°C — TRIAL 2

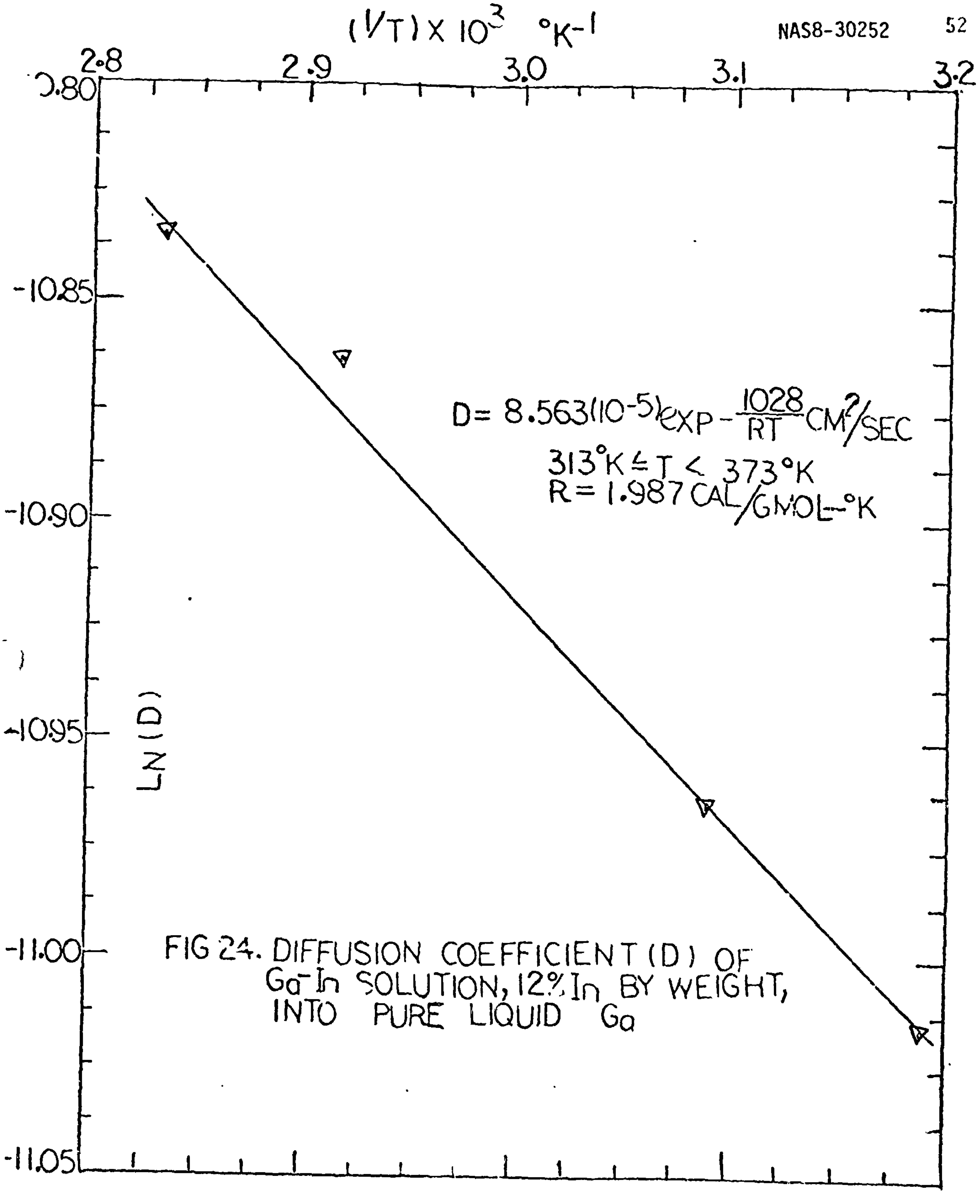


FIG 24. DIFFUSION COEFFICIENT (D) OF Ga-In SOLUTION, 12% In BY WEIGHT, INTO PURE LIQUID Ga

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APPENDIX A

ADDITIONAL DATA ON LIQUID METALS

TABLE A-1: MELTING AND BOILING POINTS OF LIQUID METALS*

METAL	MELTING POINT °C	BOILING POINT °C
Aluminum (AL)	660.37	2467
Antimony (Sb)	630.5	1750
Beryllium (be)	1278 ±5	2970
Bismuth (Bi)	271.0	1477.0
Cadmium (Cd)	321.03	765
Cesium (Cs)	28.40 ±0.1	678.4
Chromium (Cr)	1890	2482
Cobalt (Co)	1492	2900
Copper (Cu)	1083 ±0.1	2595
Gallium (Ga)	29.78	2403
Gold (Au)	1063.0	2966
Indium (In)	156.4	2087
Iridium (Ir)	2443	4527 ±100
Iron (Fe)	1535	3000
Lead (Pb)	327.3	1744
Lithium (Li)	180.54	1317
Magnesium (Mg)	651	1107
Mercuty (Hg)	-38.87	356.58
Manganese (Mn)	1244 ±3	2097
Molybdenum (Mo)	2610	5560

TABLE A-1 (cont'd)

METAL	MELTING POINT °C	BOILING POINT °C
Nickel (Ni)	1453	2732
Niobium (Nb) [Columbium]	2468 ±10	4927
Osmium (Os)	3000 ±10	5000
Platinum (Pt)	1769	3827 ±100
Plutonium (Pu)	639.5 ±2	3235 ±19
Potassium (K)	63.63	774
Rhodium (Rh)	1960	3727 ±100
Rubidium (Rb)	39	688
Selenium (Se)	217	684.9 ±1.0
Silicon (Si)	1310	2355
Silver (Ag)	960.8	2212
Sodium (Na)	97.81 ±0.03	892
Tantalum (Ta)	2996	5425 ±100
Thallium (Tl)	303	1457
Thorium (Th)	~1700	~4000
Tin (Sn)	231.91	2270
Titanium (Ti)	1675	3260
Tungsten (W)	3380	5927
Uranium (U)	1132.3 ±0.8	3818
Vanadium (V)	1890 ±10	~3000
Zinc (Zn)	419.4	907

*Ref. 4

Table A-2: PHYSICAL PROPERTIES OF SOME LIQUID METALS

Aluminum [Al, 13]

Property	Thermal Conductivity [cal/m-sec-°C]	Density [Kg/m^3]	Heat Capacity cal/kg-°C	Electrical Resistivity (μΩ cm)
Source [Ref.] / Temp °C	7	7	7	7
657				19.6
660		2380	259	
670			259	20.5
700	24.7	2369	259	
735			259	21.3
790	29.0		259	
807			259	22.4
870			259	23.2
900		2315	259	
1000			259	
1100		2261		

Table A-2: (cont'd)

Antimony [Sb, 51]

Property	Thermal Conductivity [cal/m-sec-°C]	Density [Kg/m3]	Heat Capacity cal/kg-°C	Electrical Resistivity (μΩcm)
Source [Ref.]	7	7	7	7
Temp °C				
627				117.0
630	5.2			
640		6490		
650			65.6	
700		6450	65.6	117.65
730	5.0		65.6	
800		6380	65.6	120.31
850			65.6	123.54
900			65.6	131.00
950			65.6	
970		6290		

TABLE A-2 (Cont'd)

Bismuth [Bi, 83]

Property	Thermal Conductivity [cal/m-sec-°C		Density Kg/m³		Heat Capacity cal/kg-°C		Electrical Resistivity (μΩcm)
Source Ref. / Temp °C	25	7	25	7	25	7	7
271						34.0	
280	3.472		10,050.0		36.0		
300	3.5	4.1	10,030.0	10,030.0	36.0		128.9
350	3.6111		9,970.0		36.0		
400	3.7222	3.7	9,910.0	9,910.0	36.0	35.4	134.2
450	3.8333		9,850.0		36.0		
500	3.9444	3.7	9,785.0		36.0		
550	4.0555		9,720.0		36.0		
600	4.1389	3.7	9,660.0	9,660.0	36.0	37.6	145.25
650	4.25		9,595.0		36.0		
700	4.3611	3.7	9,530.0		36.0		
750							153.53
800						39.7	
802				9,400.0			
962				9,200.0			
1000						41.9	

TABLE A-2 (Cont'd)

CADMIUM [Cd, 48]

Property	Thermal Conductivity [cal/m-sec-°C	Density Kg/m^3	Heat Capacity cal/kg-°C	Electrical Resistivity (μΩcm)
Source Ref.	7	7	7	7
Temp °C				
321				
325			63.2 63.2	33.7
330		8,010		
350		7,990		
355	10.6			
358	10.5			
380	10.5			
400		7,930		33.7
435	11.9			
500		7,820		34.12
600		7,720		34.82
700				35.78

TABLE A-2 (Cont'd)

GALLIUM, [Ga 31]

Property	Thermal Conductivity [cal/m-sec-°C	Density Kg/m3	Heat Capacity cal/kg-°C	Electrical Resistivity (μΩcm)
Source Ref. / Temp °C	7	7	7	7
29.78	7 - 9		82.0	25.9
30.3			82	27.2
32.38		6,093	82	
46.1			82	28.4
200			82	
301.0		5,905	82	
600		5,720	82	
806		5,604	82	
1100		5,445	82	

GOLD [Au, 79]

Property	Thermal Conductivity [cal/m-sec-°C	Density Kg/m3	Heat Capacity cal/kg-°C	Electrical Resistivity (μΩcm)
1063			35.55	
1100		17,240	35.55	31.34
1200		17,120	35.55	32.76
1300		17,000	35.55	34.17
1400				35.58
1500				37.0

TABLE A-2 (Cont'd)

INDIUM [In 49]

Property	Thermal Conductivity [cal/m-sec-°C	Density Kg/m3	Heat Capacity cal/kg-°C	Electrical Resistivity (μΩcm)
Source Ref. / Temp °C	7	7	7	7
156.4	9 ~ 12		65.2	
164		7,026.0		
181.5				30.11
194		7,001.0		
222.0				31.87
228		6,974.0		
271		6,939		
280.2				34.84
300		6,916.0		

TABLE A-2 (Cont'd)

LEAD [Pb, 82]

Property	Thermal Conductivity [cal/m-sec-°C		Density Kg/m3		Heat Capacity cal/kg-°C		Electrical Resistivity (μΩcm)
Source Ref. / Temp °C	25	7	25	7	25	7	7
327						39	94.6
330		3.9					
400	3.6111	3.8	10,592.0	10,510	35.2	37	98.0
450	3.6667		10,536.0		35.2		
500	3.694	3.7	10,476	10,390	35.2	37	
550	3.7222		10,419		35.2		
600	3.8055	3.6	10,360	[illegible]	35.2		107.2
650	4.0		10,300		35.2		
700	4.222	3.6	10,242		35.2		
750	4.5		10,185		35.2		
800	4.7222		10,125	10,040	35.2		116.4
1000				9,810			125.7

TABLE A-2 (Cont'd)

LITHIUM [Li^3]

Property	Thermal Conductivity [cal/m-sec-°C		Density Kg/m3		Heat Capacity cal/kg-°C		Electrical Resistivity (μΩcm)
Source Ref. / Temp °C	25	25	25	7	25	7	7
200	11.0		515	507	990	1000	
218		9					
230		9					45.25
233		9					
250	11.055		510		1001		
300	11.13888		505		1012		
350	11.1944		500		1023		
400	[illegible]25		495	490	1034		
450	11.3055		490		1045		
500	11.3611		484		1056		
550	11.4166		479		1067		
600	11.4722		474	474	1078	1000	
650	11.52777		470		1089		
700	11.5833		465		1100		
800				457			
1000				441		1000	

TABLE A-2 (Cont'd)

MAGNESIUM [Mg 12]

Property	Thermal Conductivity [cal/m-sec-°C	Density Kg/m3	Heat Capacity cal/kg-°C	Electrical Resistivity (μΩcm)
Source Ref.		7	7	
Temp °C				
651		1572	317	
678		1550		
700		1536		
720		1510		
727			321	
750		1470		
927			332	
1027			337	

TABLE A-2 (Cont'd)

MERCURY [[illegible], 80]

Property	Thermal Conductivity [cal/m-sec-°C		Density Kg/m^3		Heat Capacity cal/kg-°C		Electrical Resistivity (μΩcm)
Source Ref. / Temp °C	25	7	25	7	25	7	7
-20				13645			
0	1.8611	1.96	13590		33.4	33.34	
10	1.89166		13570		33.3		
20	1.9222		13550	13546	33.2		
50	2.01388		13470		32.9		98.4
60		2.31					
100	2.1666		13350	13352	32.8	32.79	103.2
120		2.61					
150	2.3194		13230		32.8		
160		2.79					
200	2.47222		13110	13115	32.8	32.45	114.2
220		3.03					
250	2.625		13000		32.8		
300	2.7777		12880	12881	32.8	32.34	127.5
350	2.9166		12800		32.8		135.5
400	3.01388				32.9		
450	3.0972				32.9	32.56	
500	3.1805				33.0		

TABLE A-2 (Cont'd)

POTASSIUM [K 19]

Property	Thermal Conductivity [cal/m-sec-°C			Density Kg/m3			Heat Capacity cal/kg-°C		Electrical Resistivity (μΩcm)
Source Ref.	25	17	7	25	17	7	25	7	7
Temp °C									
64									13.16
75								195.6	
100	11.11	12.4427		818	819.5	819	195		
150	11.083	11.9053		807	808.3		192		18.7
200	10.972	11.4093	10.73	795	797		189	188.7	
250	10.7222	10.9546		784	785.5	783	187		25.0
300	10.3611	10.4999	10.13	773	774.0		185		28.2
350	9.9444	10.1278		761	762.3		184		31.4
400	9.444	9.7553	9.56	750	750.6	747	183	182.6	
450	8.8888	9.3837		738	738.7		183		
500	8.3333	9.0117	8.98	727	726.7		183		
550	7.833	8.681		716	714.6	711	184		
600	7.3888	8.3503	8.46	704	702.4		184	182.5	
650	7.02777	8.0196		692	690.2		185		
700	6.75	[illegible]		681	677.8	676	185		
750		7.3995			665.4				
800								188.4	

TABLE A-2 (Cont'd)

RUBIDIUM [Rb 37]

Property	Thermal Conductivity [cal/m-sec-°C	Density Kg/m3	Heat Capacity cal/kg-°C	Electrical Resistivity (μΩcm)
Source Ref. / Temp °C	7	7	7	7
39	7.0	1475	91.3	
50	7.5		91.3	23.15
75			91.3	25.32
91.3			91.3	
100			91.3	27.47
126			91.3	

SILVER [Ag 47]

Property	Thermal Conductivity [cal/m-sec-°C	Density Kg/m3	Heat Capacity cal/kg-°C	Electrical Resistivity (μΩcm)
960.5		9300	69.2	
1000		9260	69.2	17.0
1092		9200	69.2	
1100			69.2	18.2
1195		9100	69.2	
1200			69.2	19.4
1300		9000	69.2	20.5
1340				21.0

TABLE A-2 (Cont'd)

SODIUM [Na 11]

Property	Thermal Conductivity [cal/m-sec-°C			Density Kg/m3			Heat Capacity cal/kg-°C		Electrical Resistivity (μΩcm)
Source Ref. / Temp °C	25	17	7	25	17	7	25	7	7
100	20.555	20.75170	20.55	928	926.9	928	331	330.5	9.65
150	20.0833	20.5863		916	915.3		324		
200	19.5	19.5942	19.47	903	903.6		317	320.0	13.18
250	18.805	19.0155		891	891.8	891	311		14.90
300	18.0277	18.3954	18.09	878	880.0		306		16.70
350	17.1666	17.8167		866	868.1		304		18.44
400	16.4166	17.2379	17.01	854	856.2	854	304	305.5	
450	15.7777	16.6592		842	844.2		304		
500	15.25	16.0805	15.96	829	832.2		304		
550	14.8055	15.5018		817	820.2	817	304		
600	14.4722	14.923		805	808.2		305	299.8	
650	14.25	14.3029		792	796.1		305		
700	14.1111	13.7242		780	784.0	780	305		
750		13.1455			771.9				
800								303	

TABLE A-2 (Cont'd)

THALLIUM [Tl 81]

Property	Thermal Conductivity [cal/m-sec-°C	Density Kg/m3	Heat Capacity cal/kg-°C	Electrical Resistivity (μΩcm)
Source Ref.		7	7	7
Temp °C				
303			36.7	74
306.5		11289.0	36.7	
326.7		11254.0	36.7	
330		11250.0	36.7	
333.5		11254.0	36.7	
350	5.9		36.7	
500			36.7	

TABLE A-2 (Cont'd)

TIN [Sn 50]

Property	Thermal Conductivity [cal/m-sec-°C		Density Kg/m3		Heat Capacity cal/kg-°C		Electrical Resistivity (μΩcm)
Source Ref.	25	7	25	7	25	7	7
Temp °C							
231.9							47.6
240	7.277	8.0	6985		61		
250	7.3333		6980		61	58.0	
292		8.1			61		
300	7.5555		6940		61		
350	7.7777		6905		61		
400	8.02777		6865		61		51.4
409				6834	61		
417		7.9			61		
450	8.25		6830		61		
498		7.8			61		
500	8.4722		6790		61		
523				6761	61		
550	8.7222		6755		61		
574				6729	61		
600	8.9444		6720		61		56.8

TABLE A-2 (Cont'd)

TIN[Sn, 50]

Property	Thermal Conductivity [cal/m-sec-°C		Density Kg/m3		Heat Capacity cal/kg-°C		Electrical Resistivity (μΩcm)
Source Ref. / Temp °C	25	7	25	7	25	7	7
648				6671	61		
650	9.1666		6680		61		
700	9.4166		6640		61		
704				6640			
800							62.7
1000							68.6
1100						75.8	

ZINC [Zn 30]

419.5				6920		119.9	35.3
500		13.8					35.4
600		13.6		6810		117.3	35.0
700		13.5					35.65
800				6570		107.6	35.7
900						104.4	

APPENDIX B

Table B-1: Data From Measurements At Bath Temperature 40.5°C

Water bath temperature 40.5°C
Average room temperature 30.0°C
Sol of conc In 19.96790 gm : Ga 147.48090 gm
Diffusing into solvent Ga 99.999% pure

Trial 1			Trial 2		
Time (t) sec	Weight (W) gm	$W-W_s$ m-gm	Time (t) sec	Weight (W) gm	$W-W_s$ m-gm
0	2.13280	13.00	0	2.09660	15.00
60.1	2.12765	7.85	60.0	2.09060	9.00
120.1	2.12455	4.75	120.3	2.08705	5.45
180.5	2.12265	2.85	180.5	2.08490	3.30
240.1	2.12155	1.75	240.1	2.08360	2.00
300.1	2.12085	1.05	300.2	2.08280	1.20
360.1	2.12045	0.65	360.0	2.08235	0.75
480.3	2.12005	0.25	480.3	2.08190	0.30
600.1	2.11990	0.10	600.1	2.08170	0.10
720.1	2.11985	0.05	720.2	2.08165	0.05
840.1	2.11980	~0	840.3	2.08160	~0
960.3	2.11980	0	960.2	2.08160	0
1800.0	2.11980	0	1800.0	2.08160	0
3600.0	2.11980	0	3600.0	2.08160	0
5400.0	2.11980	0	5400.0	2.08160	0

APPENDIX B

Table B-2: Data From Measurements At Bath Temperature 50.5°C

Water bath temperature 50.5°C
Average room temperature 28.5°C
Sol of conc In 19.96790 gm : Ga 147.48090 gm
Difussing into solvent Ga 99.999% pure

Trial 1			Trial 2		
Time (t) sec	Weight (W) gm	$W-W_s$ m-gm	Time (t) sec	Weight (W) gm	$W-W_s$ m-gm
0.0	2.12015	71.25	0	2.22000	65.20
30.1	2.10560	54.70	30	2.20490	50.10
60.1	2.09195	42.05	60.1	2.19320	38.40
120.1	2.07570	24.80	120	2.17750	22.70
180.0	2.06555	14.65	180	2.16820	13.40
240.1	2.05955	8.65	240	2.16270	7.90
300.2	2.05600	5.10	300.1	2.15945	4.65
360.1	2.05390	3.00	360	2.15755	2.75
420.2	2.05270	1.80	420	2.15640	1.60
480.0	2.05195	1.05	480	2.15575	0.95
600.1	2.05125	0.35	600	2.15515	0.35
720.0	2.05105	0.15	720.1	2.15490	0.10
840.2	2.05095	0.05	840	2.15485	0.05
960.0	2.05090	~0	960	2.15480	~0
1080.1	2.05090	0	1080	2.15480	0
1800.0	2.05090	0	1800	2.15480	0
3600.0	2.05090	0	3600	2.15480	0
4800.0	2.05090	0	4800.0	2.15480	0

APPENDIX B

Table B-3: Data From Measurements At Bath Temperature 70°C

Water bath temperature 70°C
Average room temperature 29.5°C
Sol of conc In 19.96790 gm : Ga 147.48090 gm
Diffusing into solvent Ga 99.999% pure

Trial 1			Trial 2		
Time (t) sec	Weight (W) gm	$W-W_s$ m-gm	Time (t) sec	Weight (W) gm	$W-W_s$ m-gm
0.0	2.12200	4.50	0.0	2.57810	497.80
30.1	2.12070	3.20	60.5	2.35685	276.55
60.3	2.12000	2.50	270.5	2.11695	36.65
90.2	2.11930	1.80	655.5	2.08120	0.90
120.1	2.11885	1.35	853.5	2.08045	0.15
150.3	2.11850	1.00	1050.5	2.08035	0.05
210.2	2.11810	0.60	1950.5	2.08030	0
360.3	2.11765	0.15	1465.5	2.08030	0
450.1	2.11755	0.05	1665.5	2.08030	0
480.2	2.11750	0	2132.5	2.08030	0
540.1	2.11750	0	3040.5	2.08030	0
751.2	2.11750	0	3447.5	2.08030	0
1290.3	2.11750	0	65640.0	2.08030	0

APPENDIX B

Table B-4: Data From Measurements At Bath Temperature 80°C

Water bath temperature
Average room temperature
Sol of conc In 19.96790 gm : Ga 147.48090 gm
Diffusing into solvent Ga 99.999% pure

Trial 1			Trial 2		
Time (t) sec	Weight (W) gm	$W-W_s$ m-gm	Time (t) sec	Weight (W) gm	$W-W_s$ m-gm
0	2.09050	125.00	0	2.20050	110.50
30.1	2.05755	92.05	30.2	2.17185	81.85
60.1	2.03360	68.10	60.1	2.15080	60.80
120.1	2.00280	37.30	120.2	2.12340	33.40
180.1	1.98590	20.40	180.0	2.10845	18.45
240.2	1.97710	11.60	240.1	2.10015	10.15
360.3	1.96885	3.35	360.2	2.09310	3.10
480.2	1.96650	1.00	480.0	2.09095	0.95
600.2	1.96580	0.30	600.1	2.09030	0.30
720.1	1.96560	0.10	720.0	1.09010	0.10
840.3	1.96555	0.05	840.0	2.09005	0.05
960.1	1.96550	~0	960.2	2.09000	~0
1080.2	1.96550	0	1080.1	2.09000	0
1800.0	1.96550	0	1800.1	2.09000	0
3600.0	1.96550	0	3600.0	2.09000	0